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Development of Quasi-Optical Gyrotrons for Fusion Plasma Heating

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This memo documents the proposed ~~NRL~~ research program on quasi-optical gyrotrons. The goal would be the design of a 1-2 MW CW source at 280 GHz to be built by industry for the purpose of heating such fusion reactors as CIT and ETR. These sources would be tunable to 30% by magnetic field and by a few percent by voltage. A prototype at slightly lower frequency would be constructed at ~~the Naval Research Laboratory~~ and this device would be experimentally characterized, ~~at NRL~~. The initial ~~NRL~~ program would last for four years and would investigate physics issues at both the cyclotron frequency and its harmonic. A follow on program lasting one to two years would design a 1 MW CW tube at 560 GHz, and experimentally characterize such a megawatt tube at slightly lower frequency.

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DEVELOPMENT OF QUASI-OPTICAL GYROTRONS FOR FUSION PLASMA HEATING

I. Introduction

The High Power Electromagnetic Radiation Branch (Code 4740) of the U. S. Naval Research Laboratory analyzes here for the Department of Energy a program of research on quasi-optical gyrotrons (QOG's) which would lead to the industrial development of megawatt power, CW relevant rf sources at frequencies from 120 to 500 GHz, on a time scale of roughly five years. These sources could ~~would~~ ~~then~~ be utilized for heating such tokamaks as CIT and ETR. At an intermediate stage, a source would be developed for heating Alcator C Mod at a frequency of 240 GHz. The overall program goal is to advance the state of the art ~~(SOA)~~ of QOG's from the proof-of-principle level to an industrially relevant rf source technology. The outstanding physics issues for QOG's would be resolved and the experimentally demonstrated performance would be increased by an order of magnitude.

The quasi-optical gyrotron is a gyrotron with an optical cavity. There is a magnetic field transverse to the axis of the cavity along which a spiraling electron beam travels. The beam gives power to the radiation reflecting back and forth and produces high power millimeter radiation at the cyclotron frequency and its harmonics. This radiation is then extracted around the sides of the mirror. The concept and the initial

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theoretical work on the quasi-optical gyrotron were done at the Naval Research Laboratory (NRL) in cooperation with the University of Maryland.[1-4] The initial experiments were done at NRL.[5,6] Figure I 1 outlines a history of the device. The initial progress of the experimental program has been slow due to both equipment and management problems. However, NRL believes it has solved both of these problems, as we discuss throughout this paper.

The quasi-optical gyrotron has a number of potential advantages over conventional cavity gyrotrons. First, since transverse mode selection is accomplished by diffraction at the mirror, only the fundamental transverse mode is excited, so that the transverse mode density is much less than in conventional cavity gyrotrons. Second, since the mirrors can be arbitrarily far apart, the heating on them can be reduced to whatever the limits of cooling technology are. Third, the radiation and electron beam are extracted at different locations, which greatly simplifies the collection of each. This is especially important if depressed collectors are used to increase the overall efficiency. Fourth, unlike the case of a conventional gyrotron, the interaction length and cavity Q are independent of each other. This gives much more flexibility in designing and optimizing the device. Fifth, the device is tunable over about 30% by varying the magnetic field, and is instantaneously tunable

over about 5% by varying the beam voltage. Sixth, the beam density can be made low[7] in a large volume, high power device (by going to a planar diode configuration and sheet beam). This reduces the effect of the AC[8] self fields, which are proportional to the local electron density.

In addition to the scientific and technical advantages of the quasi-optical gyrotron, there are also large cost and time advantages. Since the voltage is low compared to other contenders (about 80 kV), the power supply is a stock item which is available commercially. A suitable gun for the initial experiments exists and has been ordered. It is a VU 8144 (MIT) gun. The cross bore superconducting magnet is a complicated piece of high tech equipment, and difficulties with it have set back the progress of the quasi-optical gyrotron project in the past. However, we believe that these problems have been solved. The Naval Research Laboratory now has two cross bore magnets, and the proposed program intends to use both of them in separate laboratories dedicated to studing the fundamental and harmonic interaction. The collector and cooling system are common to any device. However, the low voltage beam and large area of the mirrors should minimize the cost of these components. The difficulties and costs involved with X-ray shielding should be enormously simpler for the quasi-optical gyrotron than for higher voltage devices. We estimate a cost of about $2-3/Watt for the complete commercially produced system.

Before such a tube can be realized commercially, there are a number of issues that must be resolved experimentally. So far, the quasi-optical gyrotron has achieved about 80 kW at 120 GHz in a small mirror configuration and 50 kW in a large mirror configuration. Thus, its power must be scaled up by one order of magnitude. One way which we plan to achieve this is by using initially an electron gun with about 5 times more power than in the initial experiments and ultimately a gun eight times more powerful, a gun designed for a quasi-optical system. Getting such large power in a CW relevant large cavity system will mean achieving mode control with a much denser mode spectrum. Also, the frequency must be increased by at least a factor of 2, and possibly by a factor of 4 or more. There are two possible approaches to this, and we intend to pursue both of them. First of all, one can double the magnetic field to somewhat over 100 kG. We have contacted magnet companies and they have estimated that a cross bore magnet of the proper field and physical dimension could be made in about 9 months for about $250 K. An important component of the NRL proposed program would ultimately require the purchase of such a magnet. The second option is to double the frequency by working at the harmonic with the existing magnet. Since we have a backup magnet and several electron guns and a short pulse modulator, the plan would be to set up a second laboratory to do experiments at the harmonic. These experiments

would initially be done at low power with a Varian VU8010 (Seftor) gun. Later on, a second high power gun would be required for operation at high power. The plan is to design a high power sheet beam gun for the cyclotron frequency studies and utilize the MIT gun at the harmonic. We note that the Quasi-Optical gyrotron at the second harmonic would appear to offer the only hope for producing power at 500 GHz at the megawatt level with a low voltage beam. Although the laboratories at the first and second harmonic would be separate, there would be tremendous savings from shared equipment. However, the project as proposed would require two experimental Ph.D scientists, one to focus on each harmonic. The basic strategy of the NRL program and the way it would fit into the plan for magnetic fusion is shown in Fig. I 2.

The High Power Electromagnetic Radiation Branch at NRL has had a long history of successful experimental work in high power microwave and millimeter wave source development. At present we are undergoing a reorganization. The section on thermionic beam driven sources will be reorganized under Dr. Arne Fliflet who is currently leading the Advanced Concepts and Free Electron Laser Section which recently developed a compact 100 MW pulsed gyrotron. Dr. Fliflet has contributed theoretical work to the DOE gyrotron program at NRL since 1980 and his computer codes have been used by participants in the DOE program at MIT, Varian

and Hughes. The Thermionic Beam Section will be built around two principal projects, the quasi-optical gyrotron, and a cyclotron auto-resonance maser (CARM). These projects both exemplify the laboratory's long term research goal of developing coherent high average power sub-millimeter wavelength sources which are compact and economically attractive for DoD and DOE applications. The CARM project is supported by the laboratory's ONR 6.1 core program. It will involve the development of a 250 GHz oscillator driven by a one microsecond electron beam with a voltage of 500 kV and a current of 200 Amps. This tube is expected to produce power at tens of megawatts, and could also have potential application for electron cyclotron heating of fusion plasmas. The experimental effort for the QOG will be lead by Dr. John Burke, and the experimental effort on the CARM will be led by Dr. Robert McCowan.

The remainder of this paper is organized as follows. Section II gives our perception of the possible strategies to meet the DOE requirement. Section III discusses physics of the quasi-optical gyrotron. Section IV goes into design considerations for a 1 MW device. Section V discusses experimental accomplishments up to now and plans for the future. Section VI discusses the program plan and summarizes the proposed NRL program. Appendix A discusses NRL's CARM program and its potential relevance to the DOE program. Appendix B summarizes

the qualifications and publication lists of the principal personnel involved.

1980	1981	1982	1983
Theory of Quasi-Optical Gyrotron Developed in NRL PPD Theory Branch.	Theory of Quasi-Optical Gyroklystron, NRL PPD Theory Branch and U. Md. Time dependent theory also developed.	Time dependent harmonic and mode selective harmonic theory developed at NRL PPD Theory Branch and U. Md.	
		Attempt at experiment using a home made electron gun.	Varian VU8010 electron gun used for Q.O. experiment.

1984	1985	1986	1987
Experiment on small mirror configuration done. P~100 KW, $\eta \gtrsim 10\%$	Data acquisition system installed.	Large mirror experiment P~50 KW $\eta \gtrsim 5\%$	New Magnet Arrives. VU8144 electron gun ordered.
	Magnet out for repair.		Small Mirror experiment redone.

Figure I 1

Strategy for the NRL Program

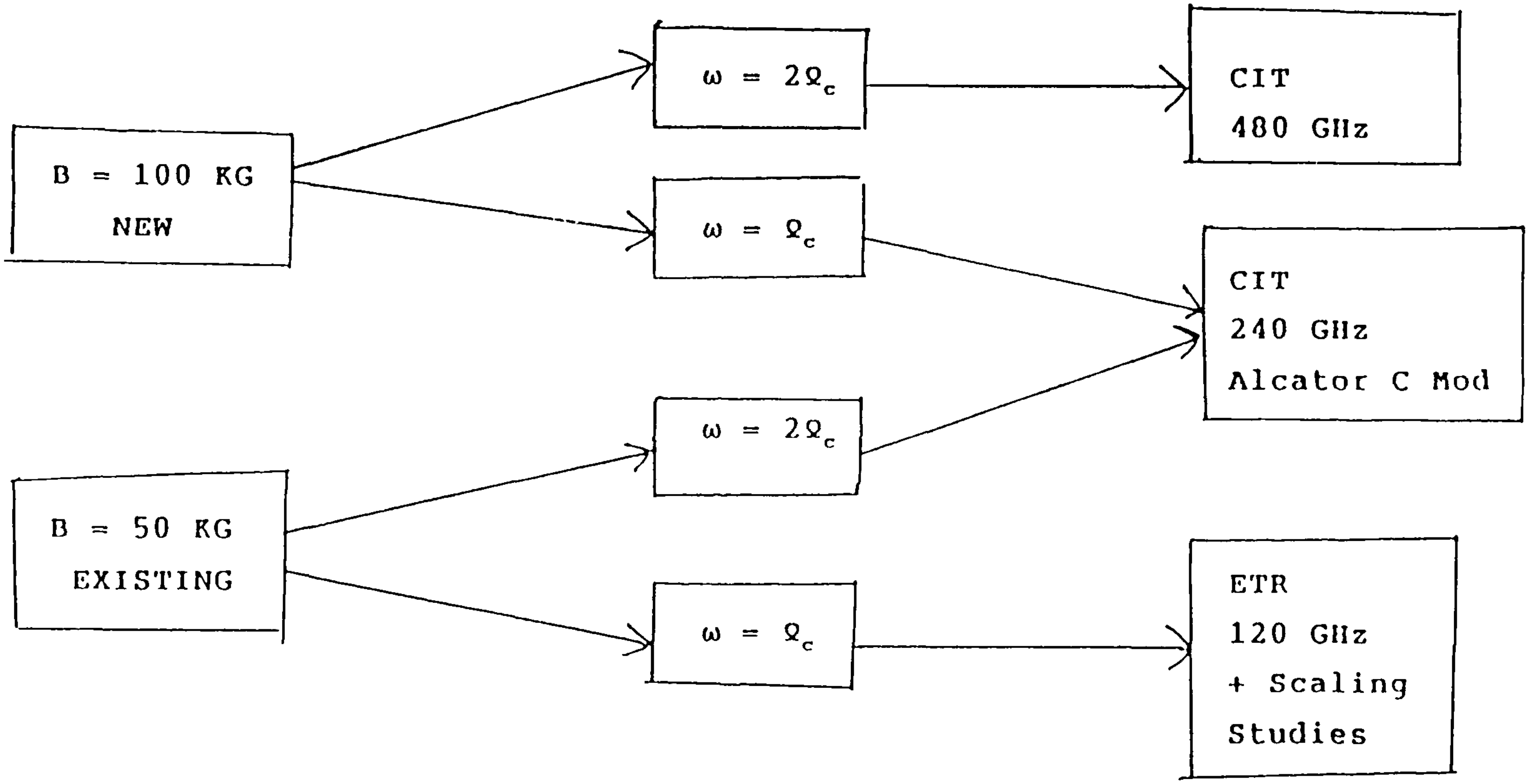


Figure I 2

II. Options for Achieving a 1 MW CW Source at 120-600 GHz

In this section, we review the various options which the DOE might pursue in developing a source to meet its requirements. The discussion here is by no means all inclusive. There are three possible sources which we feel have a chance to meet the DOE requirement of achieving 1MW in a CW relevant configuration at the frequency required, 120-600 GHz. These are gyrotrons, free electron lasers (FEL's) and cyclotron auto-resonance masers (CARM's). Of these the gyrotron is at by far the greatest state of maturity. Right now, there are commercially produced CW gyrotrons which have achieved 200 kW at 60 GHz [9] and which have achieved 100 kW at 140 GHz.[10] In an experimental gyrotron, MIT has achieved over 600 kW at 140 GHz,[11] and the Varian corporation is now building a 400 kW CW tube at that frequency.

One difficulty with the gyrotron as a tube for fusion plasma heating, is that the wall heating scales unfavorably with frequency. The MIT 600 kW tube has achieved 2 kW/cm^2 wall heating in the whispering gallery mode in which they operate.[11] The actual wall heating scales as $\omega^{2.5}$ and depends only weakly on the mode of operation, unless one operates in a very low order mode. The large wall heating density greatly complicates the achievable CW power. Furthermore, as one scales to higher frequency, one is faced with the choice scaling, at fixed mode

number, to very small cavity dimension, or scaling, at fixed cavity dimension, to much higher mode number. The former choice entails working at very high power density and compression, while the latter choice entails working with much greater mode competition. While either might be possible, each path requires some development which is not risk free. However, the cavity gyrotron has certainly advanced the furthest toward the DOE goal. This device is step tunable by the magnetic field through a series of cavity resonances and it operates in a single very high order cavity mode. The mode density does not appear great enough to tune the frequency with the voltage, so that the device, as presently configured, is not tuneable on a millisecond time scale.

The other gyrotron option being considered is the gyrotron in a quasi-optical configuration, the main subject of this proposal. So far, this gyrotron has achievedr 80 kW in a small mirror configuration,[5] and 50 kW in a large mirror configuration.[6] This configuration, we feel, comes to grips with the main difficulties of the cavity gyrotron. Specifically, the mirror heating density can be made arbitrarially small by moving the mirrors back and increasing their size. Also, the mode density can be made sufficiently large that the frequency can be controlled by the beam voltage, so that the device can have millisecond tunability over a frequency range of a few

percent. There are other advantages of the quasi-optical gyrotron also. The radiation and spent beam are extracted at different locations, so a depressed collector can be easily utilized without interfering with the radiation extraction. For instance, the depressed collector can be of virtually arbitrary size. Furthermore, the interaction length in a quasi-optical gyrotron is determined almost completely by the mirror separation and the mirror radius of curvature, while the cavity Q is determined almost completely by the physical size of the mirror. Thus, unlike a cavity gyrotron, these two crucial parameters can be set independently. The quasi-optical gyrotron also has the promised of harmonic operation. The particular advantage that it offers is that optical techniques can be utilized to select the harmonic at the expense of the fundamental. Finally, we note that since the interaction takes place in a large volume, the effect of the self fields is relatively weak at high power.

Despite the promise of the quasi-optical gyrotron, progress on its development has been slow. This has been due to a large number of equipment problems, as well as management problems at NRL. We believe that these have all been solved now. Furthermore, the development of the cavity gyrotron in the U.S. has benefitted from a successful effort in the Soviet Union. This is not true of the quasi-optical gyrotron.

Both the cavity and quasi-optical gyrotron have the great advantage of working at low voltage (about 80 kV). This allows for inexpensive power supplies and compact units. Also the X-ray shielding problem is much easier at these voltages than it is at the higher voltages being considered. The quasi-optical gyrotron, at the second harmonic, would appear to offer the only hope of operation at 600 GHz with a low voltage source. At low voltage, a depressed collector is a luxury which allows for lower cost and higher efficiency. At high voltage it is a necessity, for operation of the source, since there are no high voltage, high current, CW power supplies. Thus, the use of a high voltage driven rf source implies that the depressed collector must operate to some specified level of performance. This also entails some level of risk. Furthermore, high voltage, high current (ie several megawatt) electron guns having CW relevance have never been built. Thus, there is a significant degree of risk here also. Finally, with very few exceptions, the wave particle interaction, of high voltage sources, has not been shown experimentally to generate the sort of power or efficiency necessary for the DOE requirements. Thus, while high voltage sources are a possible answer to the DOE needs, embarking on such a development program is potentially very risky and expensive. It should certainly be recognized that low voltage sources are preferable if they could be made to work.

Moving up in voltage, the next source we consider is the cyclotron autoresonance maser (CARM). The CARM has the advantage that it utilizes the Doppler upshift so that magnetic field requirements are less than for a gyrotron, but beam energy requirements are less than for a free electron laser. The frequency that the device operates at is given roughly by $\omega \approx \gamma^2 \Omega_c$ where Ω_c is the relativistic cyclotron frequency. Thus, a 750 kV beam, and a 75 kG magnetic field allows one to achieve roughly 500 GHz without going to harmonic operation. It should be pointed out that there has been no experimental work on the CARM in this country, although there has been a significant amount of theoretical work done,[12-14] including studies of the CARM in an optical configuration (the IREC)[15]. The Soviet experimental studies of the CARM, utilizing a cold cathode generated intense pulsed beam,[16] have achieved efficiencies ranging from 2%-4%. Thus, it is clear that CARMs have a long way to go before they can be considered a solution to the DOE requirement. Below, we consider two CARM options, and briefly mention our own program in CARMs, supported by the laboratory's internal funds.

The first possible option for the CARM is the use of a CW system. For instance, one might consider a 750 kW , 15 Amp beam, assuming an efficiency of 10%. However, as just discussed, for CW application, this must be done with a depressed collector so that the the high voltage power supply does not put out

significant current. The current and perpendicular energy are low enough, and the energy is high enough, that the beam could propagate down the center of a cavity which excited a TE_{1n} mode. Thus, in addition to the difficulty the gun and depressed collector, a mode selective resonator must be made. We note that the CARM will operate in the presence of tremendous mode competition, at least as much as a gyrotron, because it must also eliminate the low frequency (gyrotron) modes.

The second option for the CARM is a burst mode, in which much higher than 1 MW is generated, but is rep rated at some low duty factor. The NRL CARM program, discussed in Appendix A, utilizes a burst mode approach because there is more relevance to military missions, which generally use rep rated sources rather than CW. The NRL program will use a 500 kV beam at 100-200 Amps. The expectation is a power of 10-20 MW at 250 GHz. In order to avoid strong space charge effects, a MIG gun will be used to produce a hollow beam. The next issue is whether to build an oscillator or amplifier. Our studies find that either one requires beam spreads of about 1% or less. These conclusions were confirmed also by numerical simulations.[12,13] In Ref. 12, for instance, it was shown by particle simulation that for the case of a 750 kV, 3 kA beam, amplifying a 90 GHz signal in the TE01 mode, the efficiency was significanly degraded if the momentum spread was 3%. The problem only gets more difficult at higher frequency.

Thus, in either an amplifier or oscillator configuration, the CARM requires very high quality beams. The NRL program has started out with an oscillator experiment for several reasons. First of all, one needs a high power source to drive an amplifier. For instance, at 20 MW and 40 dB gain, a 2 kW source at 250 GHz would be required; no small accomplishment in itself. Secondly, even with a source, one would be faced with the difficulty of preventing oscillation (the LLNL free electron laser is not faced with this problem, the pulse is so short and the length is so long that radiation cannot fill the cavity; it must run as an amplifier). Finally, one would have to launch at the input a pure mode (say the TE_{14}) in a straight pipe which has no resonant frequency or mode selective properties of its own. For these reasons, the NRL initial long pulse CARM experiment will be an oscillator configuration. If the experiment is successful in achieving 20 MW, it would have to run at a 5% duty factor to produce 1 MW for tokamak heating. Clearly, however, the CARM would have to be considered a very high risk undertaking if it were to be developed only for the heating of fusion plasmas.

Continuing up in voltage, we come to the free electron laser. These deal with multi-Megavolt electron beams, and each one is itself, a large facility. The option of producing an average power of 1-2 MW and putting ten such sources around a tokamak

simply does not exist; each one is as large as the tokamak. Thus, we are talking of single units providing all of the power. There are two FEL experiments in existence now which operate in a parameter regime which might possibly extrapolate to something which could meet the DOE requirement: one at the Lawrence Livermore National Laboratory, and one at the University of California at Santa Barbara.

The Livermore experiment has achieved 1 GW at a frequency of 35 GHz for a pulse time of 20 nsec at rep rate of 0.5 Hz. The beam which drives the FEL has a voltage of 3.5 MeV and a current of 4 kA; however, to achieve the required emittance, most of the current is scraped off and only 850A is propagated through the wiggler.[17,18] The efficiency is about 40% if one considers only the beam which traverses the wiggler. To achieve this took several years and tens of millions of dollars. It is proposed to extrapolate this FEL at least one order of magnitude in frequency and six orders of magnitude in average power so that it will be able to heat CIT. In order to do so, it is proposed to increase the rep rate to 5kHz. Other possible scale ups include going up a factor of 6 in current (to 5 kA), a factor of 3 in voltage (to about 10 MV), and a factor of 3 in pulse time (to 60 nsec).

To scale up the power of the FEL, one must first scale up the average power of the beam. At high average power, beam interception cannot be tolerated. For this reason, and also

because felt cathodes cannot run at high average power, one is forced to thermionic (most likely dispenser) cathodes.[19,20] The best results achieved on the high brightness test stand (HBTS) so far is a peak brightness of 10^6 A/(cm radian)^2 at a voltage of 800 kV and a current of 850A.[21] In the next few months tests will be done to see whether beams of 3 kA with similar brightness can be produced.

The performance of the FEL itself must also be scaled up significantly. As one goes to higher frequency, the problem of mode competition becomes more and more difficult to solve. Even at 35 GHz, with an untapered wiggler, the LLNL FEL experienced severe mode competition [22] (about half of the power in unwanted modes). Once the wiggler started its taper, however, only the desired mode continued to amplify.[18] When the experiment was attempted at 140 GHz, the mode competition became too great for acceptable operation of the amplifier. The accelerator has been dismantled, and will be attempted again in about a year and a half with an upgraded accelerator. To summarize, the Livermore program has certainly produced impressive results. However, it is our opinion that a scale up to a source capable of heating a fusion plasma would involve very significant technical risks.

The other FEL which exists in a parameter regime which could possibly scale to source capable of heating a fusion plasma is that at UCSB.[23,24] This FEL has the advantage of already

operating in the frequency range of interest to DOE, that is at more than 600 GHz. Like the Livermore program, this program also has evolved to its present capability over many years. The FEL is driven by a 6 MeV electrostatic accelerator. The maximum current propagated so far is 2.8A, although the gun is capable of generating 20A. With these parameters, about 40 kW have been produced for about 50 microseconds at a 1 HZ rep rate. Amazingly, there is virtually no mode competition; the laser operates in a single cavity mode. The interaction efficiency is only about 0.2% efficient. However, with beam recovery efficiency of 95%, the total efficiency could be as high as 2%. To scale the UCSB FEL up to a device which could heat CIT, the issue is whether the peak power could be scaled up 2.5 orders of magnitude, the average power scaled up 7 orders of magnitude, and the efficiency scaled up by at least 1 order of magnitude.

Before closing the subject of FEL's it is worth mentioning the possibility of rf accellerators driving FEL's. There are a number of such FEL programs, but most of them concentrate on much shorter wavelength than that needed for the DOE requirements. However, since rf linacs are such a well established technology, it could be worth investigating whether such an FEL could operate at 600 GHz. Such an investigation would almost undoubtedly show that, as in the case of induction linac or electrostatic accelerator driven FEL's, the present day technology is far from

what is necessary. For instance, if the conversion of microwave energy to beam (in the linac) were 50%, and then from beam to radiation (in the FEL) were 20%, this would require a 100 MW CW source at a frequency of from 1-3 GHz. Also, the problem of lethargy at the relatively long wavelengths (compared to other rf linac driven FEL's) would have to be addressed. However, an rf linac FEL, at an electron energy of about 10 MeV, may be just as attractive a candidate as FEL's driven by the other two types of driver. If such a program exists somewhere, the Department of Energy should probably pay close attention to it.

To summarize, any development path leading to a 1-10 MW source at 300-600 GHz has a considerable amount ot technological risk. However, the gyrotrons, right now, are by far the closest to meeting the DOE requirement.

III. Physics Issues of the Quasi-Optical Gyrotron

The quasi-optical gyrotron involves the application of optical techniques to gyrotron devices. Specifically, it involves the use of an optical resonator to confine the radiation. The basic configuration is shown in Fig. III 1. Here, an annular beam propagates perpendicular to the plane of the paper along a magnetic field. The radiation bounces back and forth across the length d and interacts with the beam via the conventional gyrotron mechanism. Radiation is taken out of the resonator by diffraction around the edge of the mirrors. In this section we discuss the physics of the quasi-optical gyrotron.

In any gyrotron device, one crucial physical consideration is the start current. This is always calculated in the linear regime, and it is a calculation of whether or not the power given from the beam to the radiation field exceeds the losses of the cavity. The power lost by the cavity is given by

$$P_L = \frac{\omega\varepsilon_o}{2Q} \int d^3r(E^2 + c^2B^2) \qquad \text{(III 1)}$$

where E and B are the average electric and magnetic field in the cavity. (The integral sympolizes the energy density times the volume.) The power given to the beam in the linear regime

has been calculated in a number of places. The simplest way to do this is to use the linearized Vlasov Equation to calculate the perturbed current. This, of course, is proportional to the electric field in the cavity. Then take the dot product of the perturbed current and electric field in the cavity, time average the product and integrate over volume. This gives the power lost by the beam, which can be expressed as

$$P_b = \eta\ IV = \eta_L\ E^2 IV \tag{III 2}$$

where η is the interaction efficiency in the linear regime and where η_L is defined by Eq. (III 2) and reflects the fact that in the linear regime, the efficiency is proportional to E^2. For a quasi-optical cavity, a more useful parameter than the cavity Q is the transmission at each mirror T. The two are related by $Q=2L\ \omega/Tc$, where L is the cavity length between the mirrors. In order for the gyrotron to self oscillate, it is necessary that the power out be larger than the power lost, or that the current be larger than a threshold value I_{th}.

The gyrotron, in its simplest configuration, is described by three parameters,[c] F, μ, and Δ, where, for the QO configuration,

$$F_s = \frac{E_c}{B_o} \frac{\beta_{t\,o}^{s-4}}{c} \frac{s^{s-1}}{2^{s-1} s!} \qquad (a)$$

$$\mu = 2\pi \frac{\beta_{t\,o}^2}{\beta_{z\,o}} \frac{w_o}{\lambda} \qquad (b) \qquad \text{(III 3)}$$

$$\Delta = \frac{2}{\beta_{t\,o}^2} \left[1 - \frac{s\Omega}{\omega} \right] \qquad (c)$$

Here β_t and β_z are the transverse and parallel velocity of the beam divided by the speed of light at the cavity input, w_o is the waist length of the radiation, λ is the wavelength of the radiation, ω is the angular frequency of the radiation, Ω is the relativistic cyclotron frequency at the cavity input, and s is the harmonic number. That is, F is proportional to the electric field in the cavity at the beam, μ is proportional to the cavity length along the direction of propagation of the electron beam (in the quasi optical configuration, this is in the direction perpendicular to the cavity axis), and Δ is proportional to the frequency mismatch. The standard procedure, then, is to optimize the transverse efficiency over Δ and then plot contours of transverse efficiency as a function of F and μ. Such a plot, taken from Ref. 26, is shown in Fig. III 2.

If the mode spectrum is not dense, then the way to design a quasi-optical gyrotron is clear. First one picks the optimum

mismatch by varying the magnetic field. (In the $F\mu$ plot shown, one would pick $\Delta = 0.5$.) Then one picks the physical length of the resonator so as to select that value of μ which optimizes the interaction (μ = about 18 in the $F\mu$ plot shown). Finally, one picks the value F which gives the field strength (F about equal to 0.1 in the plot shown). Let us say that the cavity has a particular value of Q. Then the value of F effectively determines the output power of the cavity. In order for the operating point to be consistent, the current must be chosen so that the output power is equal to η IV. As long as this current is larger than the threshold current, the gyrotron should oscillate in the specified mode in either pulsed or CW operation. If the current is below the threshold current, pulsed operation is unlikely, however, CW operation is theoretically possible if operation could be initiated somewhere and then adiabatically shifted to the desired mode. In the NRL program, this possibility will generally not be investigated experimentally, because we will be doing experiments with pulse lengths of 20 μsec and less.

One particularly attractive feature of the quasi-optical gyrotron is that cavity Q depends principally on the mirror size a_m, and does not depend on the radiation waist width w_o (or the parameter μ in the scaled variables). This is unlike the case of a cavity gyrotron in which the Q and radiation

waist are largely constrained by the diffraction limit. Thus, if such a quasi-optical gyrotron is made to work at low power and low current, the scaling to high current and high power is very simple, just increase the current and decrease the Q so that IQ is constant. The wave particle interaction is exactly the same as in the lower power case, but additional power output is fed by additional current. This scaling is an important aspect of the quasi-optical gyrotron, and an early milestone of any development program would be to test it experimentally. This could be done in pulsed experiments in small cavities at both high and low power. The problem in working at high power, CW, is that heating on the mirror could be significant.

The solution to the problem of mirror heating is to move the mirrors back and make them larger, so that wall loading on them is reduced. However, in a large cavity configuration, the mode spectrum is quite dense, and one is no longer free to pick the desired mode just by picking the magnetic field. Thus, in the high power CW case, a way must be found to select the proper mode in a dense spectrum. One way to do this is with the use of a prebunching cavity, a cavity which is small, and therefore mode selective. This is shown schematically in Fig. III 3. The cavity would be excited, at low amplitude and with controlled phase, in the desired mode by the output of the main

cavity. Thus, although the configuration looks like a klystron, it is still an oscillator configuration, and is more like a complex cavity gyrotron rather than a gyroklystron amplifier. A simulation code developed at NRL and the University of Maryland[2] can examine the time dependent behavior of such a configuration. The values of electric field as a function of normalized time for the gyrotron and gyroklystron configurations are shown in Fig. III 4. It is clear that without mode control, the gyrotron in that particular simulation was quite multimoded. However, the gyroklystron generally operated in a single moded fashion. The mode separation in those similations was one half of one percent. In addition to allowing for mode selectivity, the gyroklystron configuration also was found to enhance the efficiency of the interaction. In Fig. III 5, taken from Ref. 2, are tabulated efficiencies of a series simulations of gyrotron and gyroklystron/complex cavity configurations.

One significant hurdle in any experiemental program is the design of the feedback system which would take power from the output to the prebunching cavity. Assuming a Cassegrain[6] output system a conceptual design is shown in Fig. III 6. The output radiation is taken around the edge of the mirror, collected and focused into a Gaussian beam. Then a small part of this power is taken off and transmitted through a

piezoelectric crystal in which the output radiation phase is controlled by a voltage across the crystal (mechanical phase control is also possible, but less desirable). A voltage controlled attenuator would also control the amplitude of the radiation as it is fed back into the prebunching cavity. Then the Cassegrain system is reversed and used as an input to the prebunching cavity. The prebunching cavity would have a much higher Q than the output cavity, so that even though excited at low power, the field in the input cavity would be some fair fraction of the field in the output cavity.

An important part of the research program proposed by NRL is the exploitation of the potential of the quasi-optical gyrotron at both the fundamental and harmonic. The theory at the harmonics was developed also at NRL and the University of Maryland.[3,4] It has shown that for second harmonic operation, the theoretical efficiency in the steady state case is roughly the same as in the fundamental, however, the high efficiency is realized at larger electric fields. In Fig. III 7 are shown steady state calculations of efficiency as a function of electric field for harmonic number n for both gyrotron and gyroklystron configuration. By sacrificing some efficiency and working closer to the harmonic, it is shown in Fig. III 8 that the fields can be reduced. The time dependent theory of the harmonics has also been worked out. In Fig. III 9 are

tabulated results of efficiencies from several simulations[3] of quasi-optical gyrotrons and gyroklystrons.

A difficulty with the harmonic, however, is how one suppresses the fundamental, which would normally dominate. The use of optical techniques allows for the potential of fundamental frequency suppression schemes which are not available in a conventional cavity gyrotron. The simplest way is to exploit the fact that as the frequency increases, the spot size w_o decreases in a given resonator. Thus, the diffraction losses are greater at the fundamental and this can be used for fundamental frequency suppression.[4] Specifically, if the transmission coefficient at harmonic m is T_m, then for a Gaussian beam, the transmission at harmonic n is $T_n = (T_m)^{n/m}$. In Ref. 4, starting currents were calculated. Typically, for the beam voltages applicable, the starting current for the fundamental could be as much as a factor of two higher than for the harmonic. However, the operation of a gyrotron so close to its start current generally means operation at low efficiency. However, it is probably the simplest way one can achieve second harmonic operation. Another purely optical means to supress the fundamental frequency would be the use of a grating instead of one of the mirrors.[27] This is a fairly standard technique for lasers and is illustrated in Fig. III 10.

For a quasi-optical gyrotron to work at the harmonic at high efficiency while suppressing the fundamental would undoubtedly involve prebunching of the beam at the second harmonic. A prebunching scheme similar to that of Fig. III 6, but which also filtered out the fundamental frequency, would have to be developed. Such a scheme is shown schematically in Fig. III 11, where a grating is added to the feedback path. The use of a prebunched beam at the second harmonic not only enhances the efficiency, it also decreases the start current by strengthening the interaction. If the linear efficiency at the harmonic is denoted η, it can be expressed as the sum of a gyrotron part η_G and a gyroklystron part η_K. These are written out for the second harmonic in Fig. III 12.

The situation can be summarized in the following way. To suppress the fundamental, the actual current I must be less than the transmission at the fundamental T_1 times a constant which we denote I_1. To excite the harmonic, I must be larger than the transmission at the harmonic T_2 times another constant I_2. Since $T_2 = T_1{}^2$, the region of harmonic operation is above a parabola, while the region of fundamental suppression is below a line. This is shown schematically in Fig. III 13 in I-T space. The use of prebunching at the harmonic extends the power range for which harmonic operation is possible.

QUASI-OPTICAL RESONATOR CONFIGURATION

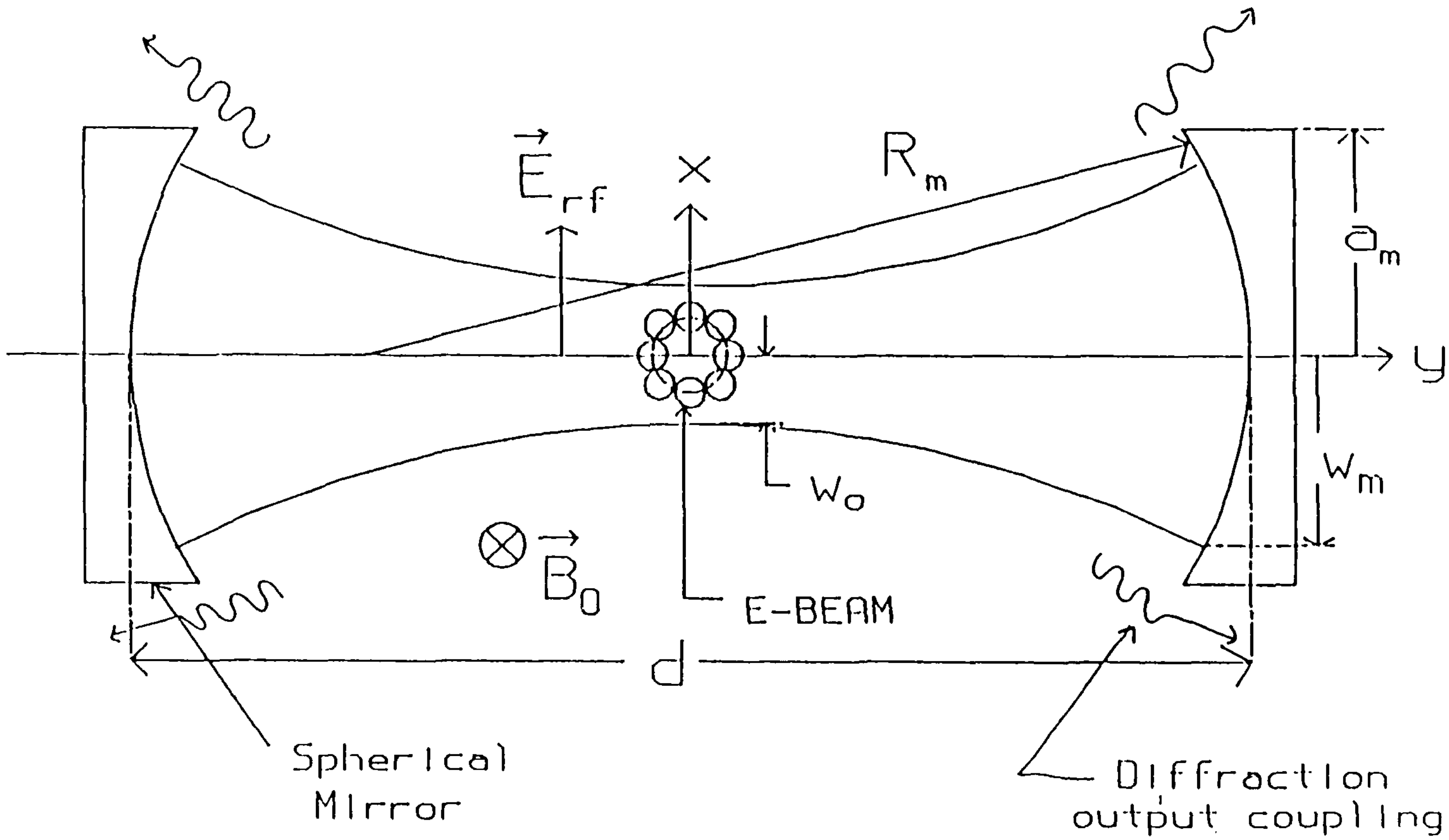


Figure III 1

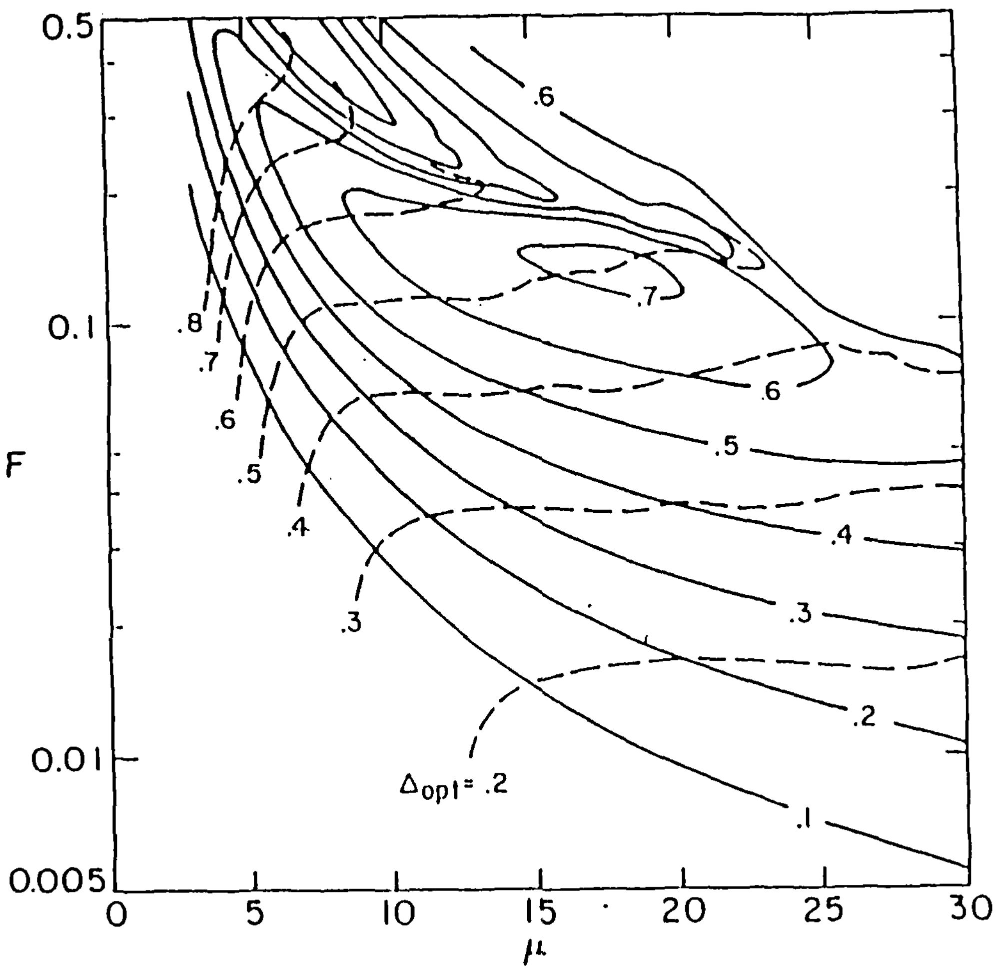


Figure III 2

120 GHz QUASI-OPTICAL GYROTRON

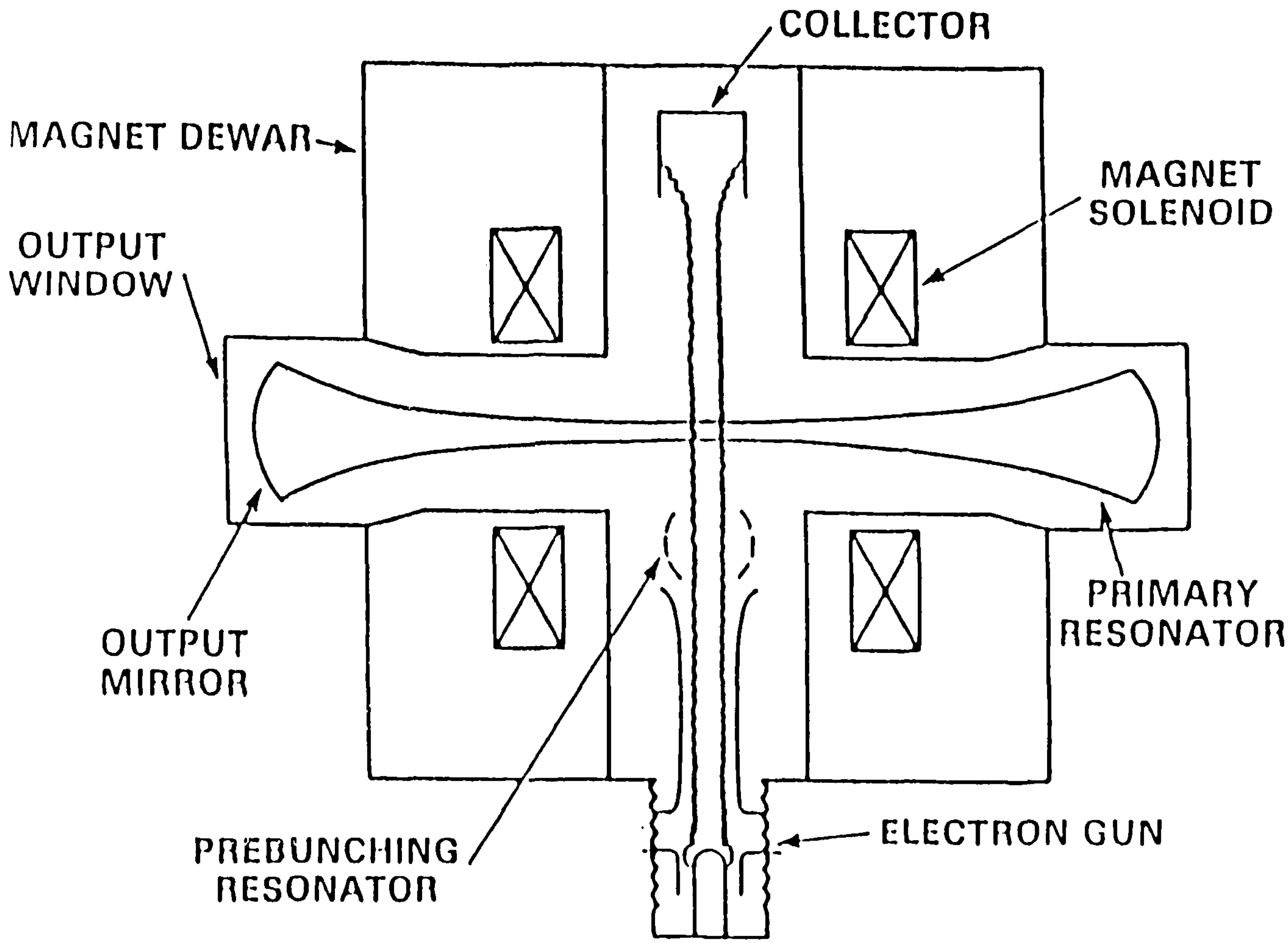
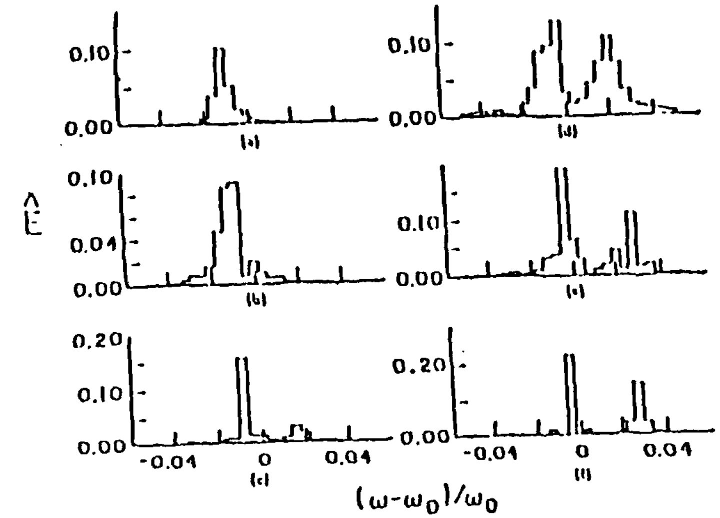
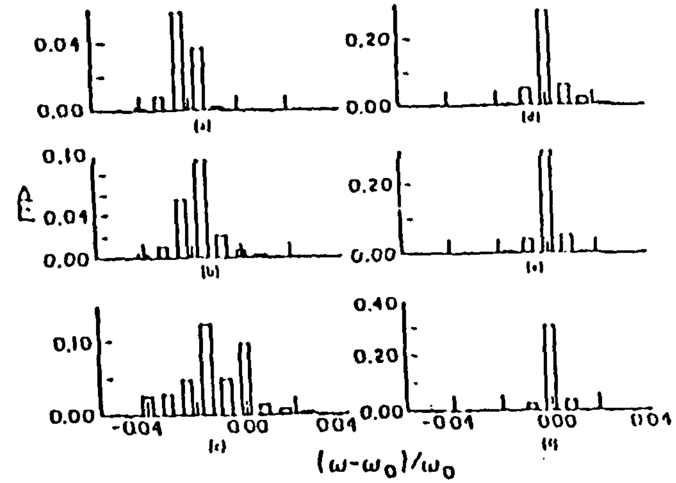


Figure III 3



Normalized electric field amplitudes $\hat{E}_l = \sqrt{\pi} e r_0 E_l / mc^2$ at different values of normalized time $\hat{t}$ for a single-cavity quasi-optical gyrotron, with $\hat{\Omega} = 1.096$ a constant in space. (a), $\hat{t} = 2$, $\eta = 0.069$; (b), $\hat{t} = 5$, $\eta = 0.071$; (c), $\hat{t} = 10$, $\eta = 0.104$; (d), $\hat{t} = 20$, $\eta = 0.229$; (e), $\hat{t} = 40$, $\eta = 0.222$; (f), $\hat{t} = 75$, $\eta = 0.263$. The equilibrium has two modes with large amplitudes. The high-frequency band has been nonlinearly destabilized.



Time history for a klystron with a 4-A circular beam, with $k_\perp r_w = 5.037$ and decreasing from 1.134 to 1.014. The prebunching is done at frequency ω_0. (a), $\hat{t} = 2$, $\eta = 0.0$ (b), $\hat{t} = 5$, $\eta = 0.061$; (c), $\hat{t} = 10$, $\eta = 0.133$; (d), $\hat{t} = 15$, $\eta = 0.359$; (e), $\hat{t} = 25$, $\eta = 0.367$, (f), 50, $\eta = 0.370$. The modes that interact weakly with the beam are almost completely pressed.

Figure III 4

Summary of Multi-Mode Analysis

I/100T (Amps)	Gyrotron or Gyroklystron	η (Annular beam)
2	G	Below I (Start)
	K	35
4	G	19
	K	37
8	G	24
	K	38
16	G	29

T = Transmission through each mirror

Figure III 5

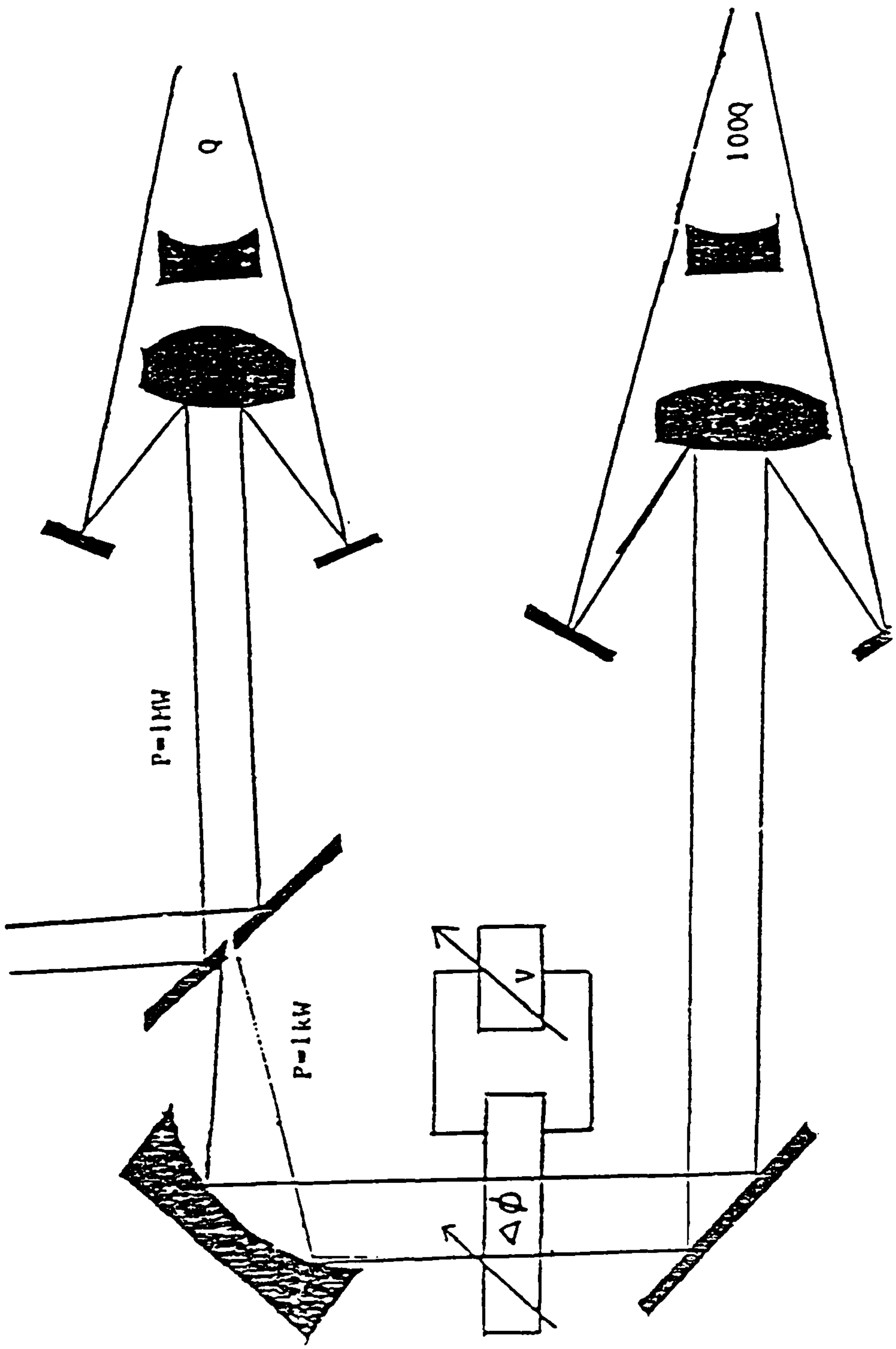
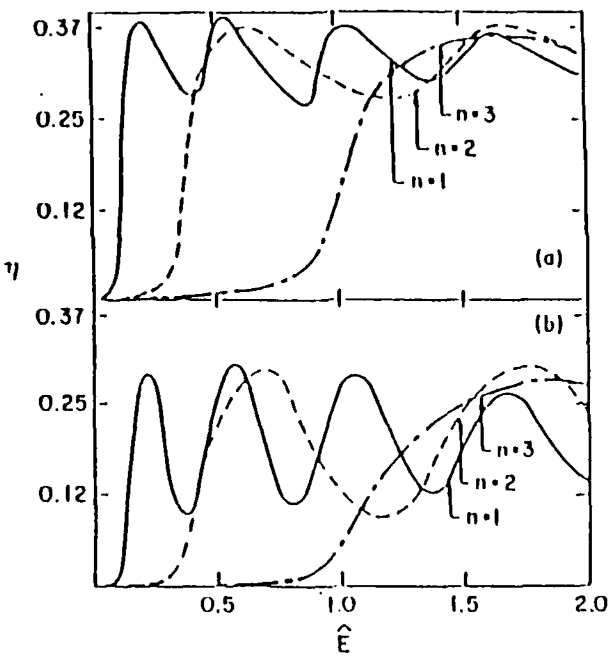
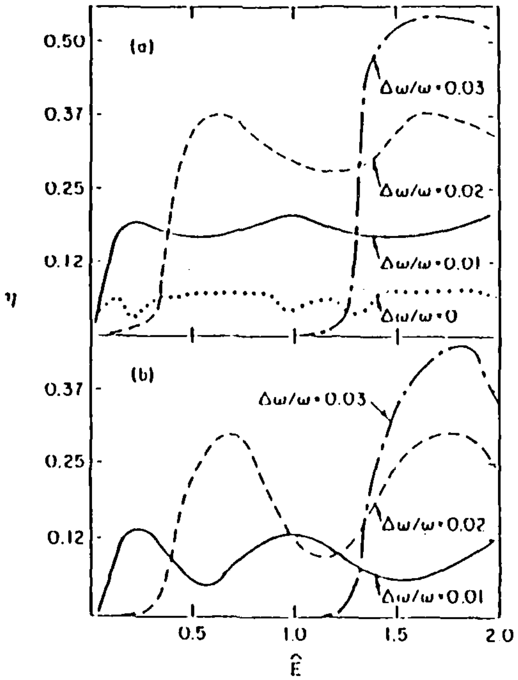


Figure III 6



Efficiency as a function of normalized electric field for a pencil beam with $\gamma_0 = 1{\cdot}118$, $\alpha_0 = 1$ (radian), $r_{02}/\lambda = 7{\cdot}2$, and $\Delta B/B_n = -8\%$ and (*a*) gyro-klystron device and (*b*) single cavity gyrotron. Solid, dashed, and dot-dashed lines represent first, second, and third gyrocyclotron harmonic, respectively.

Figure III 7



Efficiency as a function of normalized electric field for different values of detuning parameter $\Delta\omega/\omega$. The magnetic field is constant across the interaction region ($\Delta B/B_0 = 0$) and $n = 2$; all other parameters are the same as in Fig. 3. In (*a*) gyroklystron and in (*b*) single cavity, gyrotrons are presented with dotted, solid, dashed, and dot-dashed lines for $\Delta\omega/\omega = 0$, 0·01, 0·02 and 0·03, respectively.

Figure III 8

The Quasi-Optical also has the potential of working at harmonics of ω_o/γ.

100 I/T	V(kV)	Gyrotron η	Gyroklystron η
7.4	60	7 †	29
	120	13	14
14	60	18	*
	120	14	17
20	60	20	
	120		

† No steady state.

* Does not settle into prebunched mode.

Figure III 9

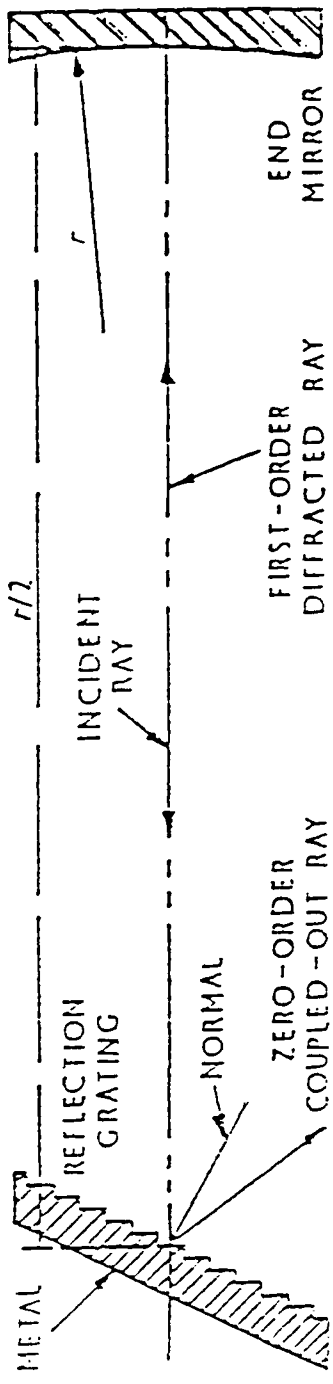


Figure III 10

The Start Current at the Second Harmonic can be further reduced by Prebunching the Beam.

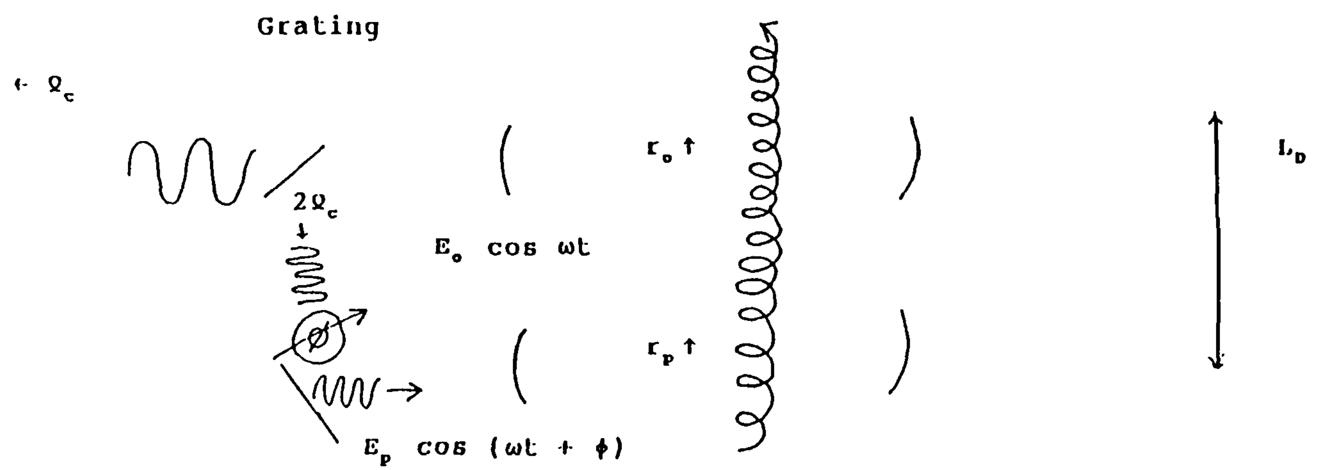


Figure III 11

LINEAR THEORY AT THE HARMONIC

$$\eta_G = \frac{\pi}{4}\,\frac{1}{(\gamma_o - 1)\gamma_o}\left(\frac{E_o}{B}\right)^2 \xi_o^{\,2}\left(\frac{\Omega_o}{\omega}\right)^2 J'_n\,(\zeta_o)\exp\left[-\left(\xi_o\,\frac{\Delta\omega}{\omega}\right)^2\Big/2\right]$$

$$\times\left[\frac{\beta_\perp\,2\Delta\omega}{2\omega}\,\xi_o^{\,2}\,J'_n(\zeta_o) + \zeta_o J_n(\zeta_o)\left(1 - \frac{n^2}{\zeta_o^{\,2}}\right)\right]$$

$$\eta_k = \frac{e\,r_o\sqrt{\pi}\,E_o p_\perp q}{4p_z}\,\exp\left[-\frac{(2\Omega_o - \gamma\omega)^2\,r_o^2 m^2}{4p_z^{\,2}}\right]\sin\left[\phi - \frac{m(2\Omega_o - \gamma\omega)L}{p_z}\right]$$

$$q = \frac{\sqrt{\pi}}{2}\quad\frac{\omega p_\perp e\,E_p r_p L_D}{p_z^2\,c^2}\,J'_2\,(\zeta)\,\exp\left[-\frac{(2\Omega_o - \gamma\omega)^2 r_p^{\,2} m^2}{4p_z^{\,2}}\right]$$

$$\zeta_o = \frac{kp_\perp}{m\Omega_o} \qquad\qquad \xi_o = \left(\frac{r_o\omega}{V_z}\right)$$

$$\eta = \eta_G + \eta_K$$

Figure III 12

Suppress fundamental: $I/T_1 < I_1$

Excite harmonic: $I/T_2 = I/T_1^{\,2} > I_2$

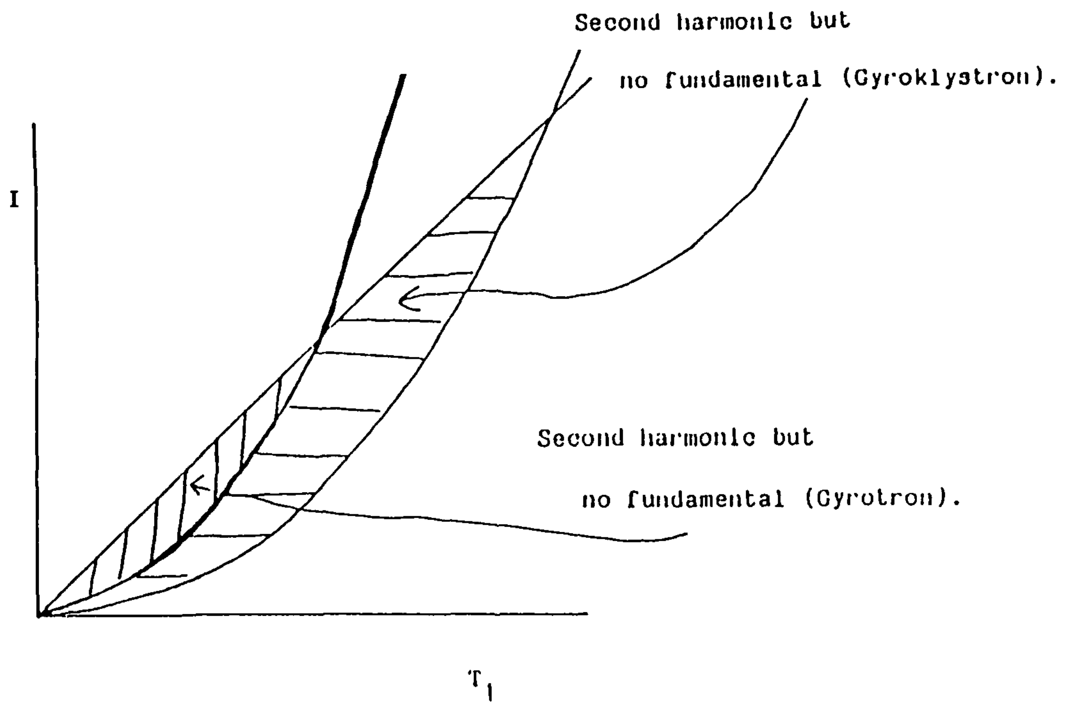


Figure III 13

IV. DESIGN CONSIDERATIONS FOR 280 AND 560 GHz, 1 MW QUASI-OPTICAL GYROTRONS

Introduction

In this section our approach to the design of 1 MW 280 GHz or 560 GHz quasi-optical gyrotrons is outlined. The design considerations presented here parallel those given for a 1 MW conventional cavity gyrotron.[28] The QOG differs from conventional gyrotrons by having an open resonator formed by a pair of spherical mirrors as shown in Figure IV 1 which defines the basic parameters of the resonator. Ouput coupling occurs via diffraction around the edges of the mirrors. A strip electron beam is the optimum configuration, but most design issues can be studied by means of an annular beam as used in conventional gyrotrons. Such a beam is indicated in Fig IV 1.

The point designs obtained in this Section are for single cavity resonators. This is the simplest Q-O configuration and forms the starting point for more complicated designs with, for example, prebunching cavities. An important objective of this design exercise is to show that ohmic heating constraints can be satisfied by the QOG at the specified frequencies and output power. These designs also show the minimum axial mode density for these operating regimes and highlight the need for development of positive mode selection techniques. Additionally, the issue of space-charge effects for e-beam propagation in an open resonator are addressed.

Quasi-Optical Gyrotron Beam-Wave Interaction theory

The linear and non-linear theory of quasi-optical and waveguide gyrotrons has received considerable attention.[1-4] The use of normalized variables to reduce the gyrotron equations of motion to a small number of parameters has proven extremely useful for the design optimization of waveguide gyrotrons. This enables the operation of a wide class of gyrotrons to be expressed in terms of F-μ plots in which the contours of constant transverse efficiency (η_t) are plotted as a function of the normalized wave amplitude and interaction length for optimized resonance detuning. The transverse efficiency is related to the interaction efficiency according to: $\eta = \beta_{to}^2 \eta_t / [2(1-\gamma_o^{-1})]$. As shown by Danly and Temkin,[26] the normalized wave amplitude (F_s), interaction length (μ), and current (I) parameters occurring in the standard gyrotron theory can be expressed in terms of the QOG parameters as follows (in MKS units):

$$F_s = \frac{E_c \beta_{to}^{s-4}}{B_o c} \frac{s^{s-1}}{2^{s-1} s!} \qquad \text{(a)}$$

$$\mu = 2\pi \frac{\beta_{to}^2}{\beta_{zo}} \frac{w_o}{\lambda} \qquad \text{(b)} \qquad \text{(IV 1)}$$

$$I = \frac{e \ \beta_{to}^{-2(3-s)}}{\pi^4 \varepsilon_o \gamma_o m c^3} \frac{\lambda}{d} \left(\frac{\lambda}{w_o}\right)^2 \left(\frac{s^s}{2^s s!}\right)^2 QI_A \qquad \text{(c)}$$

where s is the harmonic number, λ is the wavelength, w_o is the radiation beam waist, E_c is the rf E-field at the beam, B_o is the applied axial magnetic field, d is the mirror separation, γo is the beam relativistic factor, and β_{to}, β_{zo} are the transverse and axial beam velocities normalized to c, the speed of light at the cavity input. The eletron mass is denoted by m, e is the electron charge, I_A is the dc beam current in Amps, and Q is the cavity Q factor. Assuming a single rf mode and a pencil beam, the optimum values of F_s and μ for the QOG can be found from an F-μ plot for the optimized detuning parameter:

$$\Delta = \frac{2}{\beta_{to}^2}\left(1 - \frac{s\Omega}{\omega}\right) \qquad \text{(IV 2)}$$

where Ω is the relativistic cyclotron frequency at the cavity input. The required normalized beam current is then given by:

$$I = \frac{F^2}{\eta_t} \qquad \text{(IV 3)}$$

Parameter choices for the Q-O gyrotron must account for multimode effects since usually the axial mode frequency separation is much less than the optimum resonance detuning. This means that if the magnetic field is chosen such that the detuning parameter is optimized for the desired operating mode ($\Delta=\Delta_{opt}$), then the detuning parameter for a competing mode may have a value corresponding to the minimum starting current condition

($\Delta \approx \Delta_{min}$). Thus the competing mode would have a lower starting current than the desired operating mode leading to mode competition. Investigations of multi-mode effects have been carried out at NRL using a time dependent multimode code[2,3]. These calculations have tended to show that efficient single mode steady states can be obtained under multi-mode conditions, but that multiple mode steady states can also result depending on the magnetic field taper and other effects. Clearly, the need to control mode competition signifigantly impacts the choice of optimum design parameters. Values of the F and μ parameters for first and second harmonic operation found to be optimum from multimode simulations are shown in Figures IV 2 and IV 3. These values have been used as starting points to base the present designs.

Output Power Scaling

The output power of the Q-O gyrotron scales as:

$$P(W) = \frac{\pi m^2 c^2}{16 Z_o e^2} \gamma_o^2 \beta_{zo}^2 \beta_{to}^{4-2s} \left(\frac{2^{s-1} s!}{s^s} \right)^2 \mu^2 \; F_s^2 \; T \qquad \text{(IV 4)}$$

in MKS units, where T is the resonator total output coupling (that is twice the coupling at each mirror), γ_o is the beam relativistic factor, s is the harmonic number, and β_{to}, β_{zo} are the transverse and axial beam velocities normalized to c.

Choosing μ to optimize efficiency leads to a trade-off between F_s and T for given output power and beam parameters. This trade-off is shown for a 1 MW device operating at the first or second harmonics with μ=18 in Figures IV 4 and IV 5. The choices of F_s and T used to obtain point designs for a first harmonic device at 280 GHz and a second harmonic device at 560 GHz are indicated by the solid dots.

Ohmic Heating of Resonator Mirrors

It is convenient to express the average mirror heating density for the first or second harmonic in the form:

$$\rho_{ohm}(W/m^2) = 4.1\times10^{-15}\ \sigma^{-0.5}\ \omega^{2.5}\ \gamma^2\ \beta_t^{8-2s}\ \frac{1+g_m}{\ln(T_m^{-1})}\ F^2 \qquad \text{(IV 5)}$$

where $g_m = 1 - d/R_m$ and T_m is the (single) mirror output coupling coefficient, σ is the mirror conductivity which is taken to be 3.6×10^7, and ω is the wave angular frequency. For a given frequency, F, beam parameters, and output coupling, mirror heating depends on g_m. The peak ohmic heating density occurs at the center of the mirror and is related to the average heating density according to: $\rho_{peak}=\ln(T_m{}^{-1})\rho_{av}$, which shows that the difference between the peak and average heating can be minimized by maximizing the mirror output coupling. The parameter g_m can vary from 1 (planar mirrors) to -1 at which point the resonator

becomes unstable. As the frequency is increased, ohmic heating can be controlled by choosing g_m close enough to -1. Since the radiation beam waist is determined by optimum interaction length, the mirror separation increases as g_m approaches -1. Thus, the price for reduced ohmic heating is increased axial mode density. For a given frequency and e-beam parameters, a constraint on heating density leads to a trade-off between g_m and T_m ($T=2T_m$). Note that for a given output power and μ, F is also determined by T. The relation between g_m and T for a first harmonic device at 280 GHz with 2 kW/cm^2 average heating is shown in Figure IV 6. The corresponding plot for a second harmonic 560 GHz device with the same heating density is shown in Figure IV 7. The choices for g_m used in the point designs are indicated by dots: i.e., $g=-0.54$ for the 280 GHz design and $g_m=-0.96$ for the 560 GHz design. Clearly, the 560 GHz resonator is much closer to the unstable limit.

The prescription for resonator design can be summarized as follows: Efficiency optimization studies determine F and μ. The starting point is the single mode F-μ plot; however, B-field tapering and beam prebunching can increase the available parameter space. Next, the output power and electron beam parameters determine T. Then ohmic heating and operating frequency determine g. This completely determines resonator configuration.

Electron beam propagation

Space-charge effects become important at high beam currents. The calculation of space-charge effects in waveguide gyrotrons can be estimated using a 1-D analysis. The calculation of space-charge effects is more complicated in the case of a QOG, particularly when an annular beam is used, because e-beam propagation across an open resonator depends on 2-D effects. We have used the Herrmannsfeldt Electron Trajectory Code to investigate space-charge effects associated with an annular 80 kV, 60 Amp beam. The beam dimensions correspond to the Varian 8144 electron gun developed for the MIT 1 MW, 120 GHz gyrotron experiment applied to a 120 GHz QOG configuration. The axial magnetic field was reduced to 10 kG in order to avoid excessively large mesh point arrays. Space-charge effects are not expected to be very sensitive to variation of the magnetic field as long as the Larmor radius is signifigantly less than the average beam radius. Typical Herrmannsfeldt code results are shown in Figures IV 8, IV 9, and IV 10. Figure IV 8 shows the electron trajectories traversing the open resonator region. Figure IV 9 shows the momentum pitch ratio α plotted as a function of axial distance for 5 electron trajectories. Figure IV 10 shows the equipotentials in the resonator region. The initial α of the beam electrons in the gun drift tube is 1.25. The applied magnetic field is held constant in the resonator. As shown in

Figure IV 9, α increases to over 1.5 in the middle of the resonator due to space-charge effects. Figure IV 10 shows that the electron beam energy is depressed by about 10 kV due to space-charge. This drop in beam energy could be avoided by applying an accelerating voltage across the resonator. Preliminary calculations indicate that this approach also improves beam quality in the resonator. In summary, our calculations indicate that space-charge effects must be taken into account in the design of a 1 MW device, but should not signifigantly degrade the device efficiency.

Point Designs

Point designs have been obtained for a 280 GHz fundamental harmonic QOG and a 560 GHz second harmonic QOG with output powers of 1 MW and 2 kW/cm^2 average mirror heating. The parameters are given in Tables IV 1 and IV 2, respectively. (If larger mirror loading were tolerable, the parameters of a 1 MW device would be less constrained.) These are intended to serve as a guide to the experimental research program by pointing out the major design trade-offs. The physics issues associated with these devices have been discussed in Section 3.

The radiation waist of the 280 GHz design is 0.5 cm which is compatible with use of an annular electron beam produced by the Varian VUW-8144 electron gun. Due to the smaller beam waist

(0.25 cm), a strip electron beam will be required for the 560 GHz device.

It is interesting to compare the 280 GHz and 560 GHz designs. In order to satisfy the same average heating constraint, the 560 GHz design has twice the physical mirror separation as the 280 GHz design which leads to a four times higher axial mode density. The larger mirror separation together with the lower output coupling coefficient necessary for second harmonic operation leads to a Q of 153,000 for the 560 GHz design compared to 8,400 for the 280 GHz design. The larger mirrors needed by the 560 GHz design (3.2 cm vs. 1.3 cm) leads a higher total mirror heat dissipation (64 kW vs. 10 kW) although this is still only 6% of the total output power. Finally, the need for lower output coupling leads to higher peak mirror heating for the 560 GHz design (6.4 kW/cm^2 vs. 3.5 kW/cm^2).

The basic conclusion of this design study is that a 1 MW 280 GHz QOG is a relatively straight forward extrapolation of previous design studies. The 560 GHz design is considerable more difficult but there do not appear to be any insurmountable obstacles.

Table IV 1

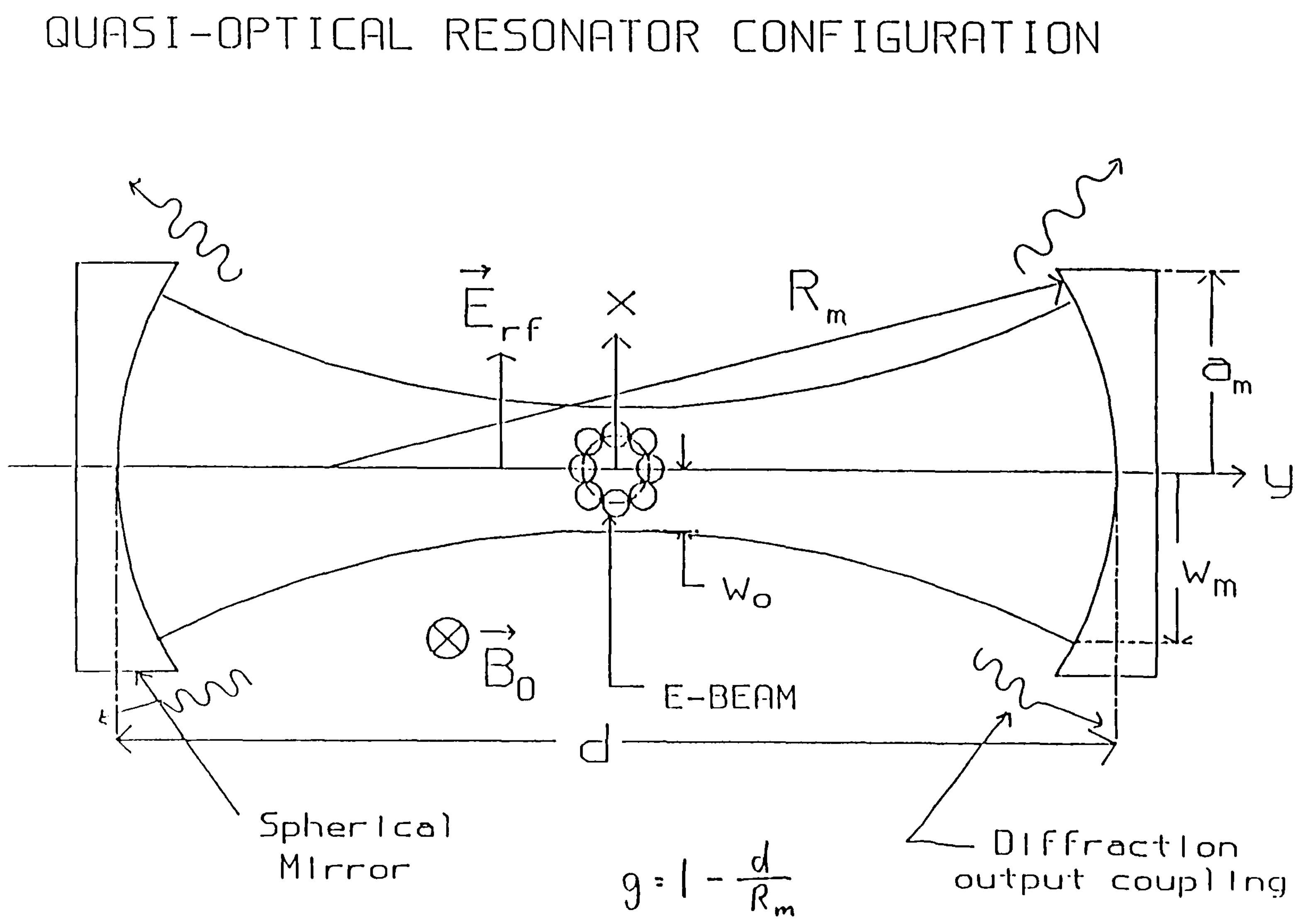
280 GHZ, 1 MW Q-O GYROTRON DESIGN

Normalized Circuit Parameters	
$\mu = 18$	
$F = 0.06$	
Applied Magnetic Field	11.6 T
Beam Parameters	
Voltage	80 kV
Current	50 Amp
Pitch Ratio	1.5
Diameter	1 cm
Cavity Parameters	
Mirror Separation	25 cm
Mirr. Rad. of Curv. (g_m=-0.52)	16 cm
Mirror Radius	1.3 cm
Total Output Coupling Coef. (T)	35 %
Rad. Beam Waist ($w_o = 4.6\lambda$)	0.5 cm
Diffraction Q	8,400
Average Heating Density	2 kW/cm2
Peak Heating Density	3.5 kW/cm^2
Mirror Heat Dissipation	10 kW
Mode Frequency Separation ($\Delta f/f$)	0.2 %
No. of Interacting Modes	~ 7
Annular Beam Efficiency	≃25 %

Table IV 2

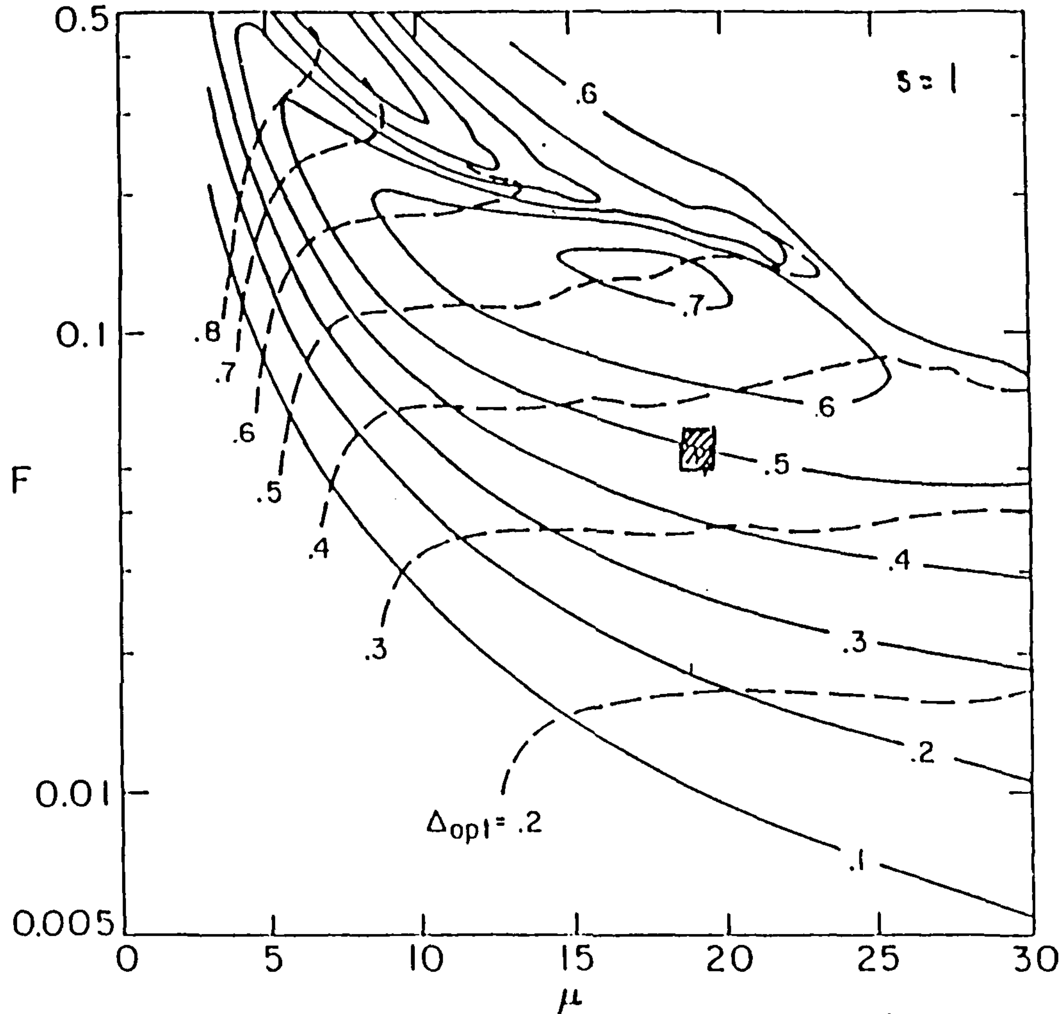
560 GHZ, 1 MW 2nd HARMONIC QOG DESIGN

Normalized Circuit Parameters	
$\mu = 18$	
$F = 0.05$	
Applied Magnetic Field	11.6 T
Beam Parameters	
Voltage	80 kV
Current	60-120 Amp
Pitch Ratio	1.5
Cavity Parameters	
Mirror Separation	50 cm
Mirr. Rad. of Curv. (g_m=-0.96)	25.5 cm
Mirror Radius	3.2 cm
Total Output Coupling Coef. (T)	8.2 %
Rad. Beam Waist ($w_o = 4.6\lambda$)	0.25 cm
Diffraction Q	153,000
Average Heating Density	2 kW/cm2
Peak Heating Density	6.4 kW/cm^2
Mirror Heat Dissipation	64 kW
Mode Frequency Separation ($\Delta f/f$)	0.05 %
No. of Interacting Modes	~ 28
Efficiency	10-20 %



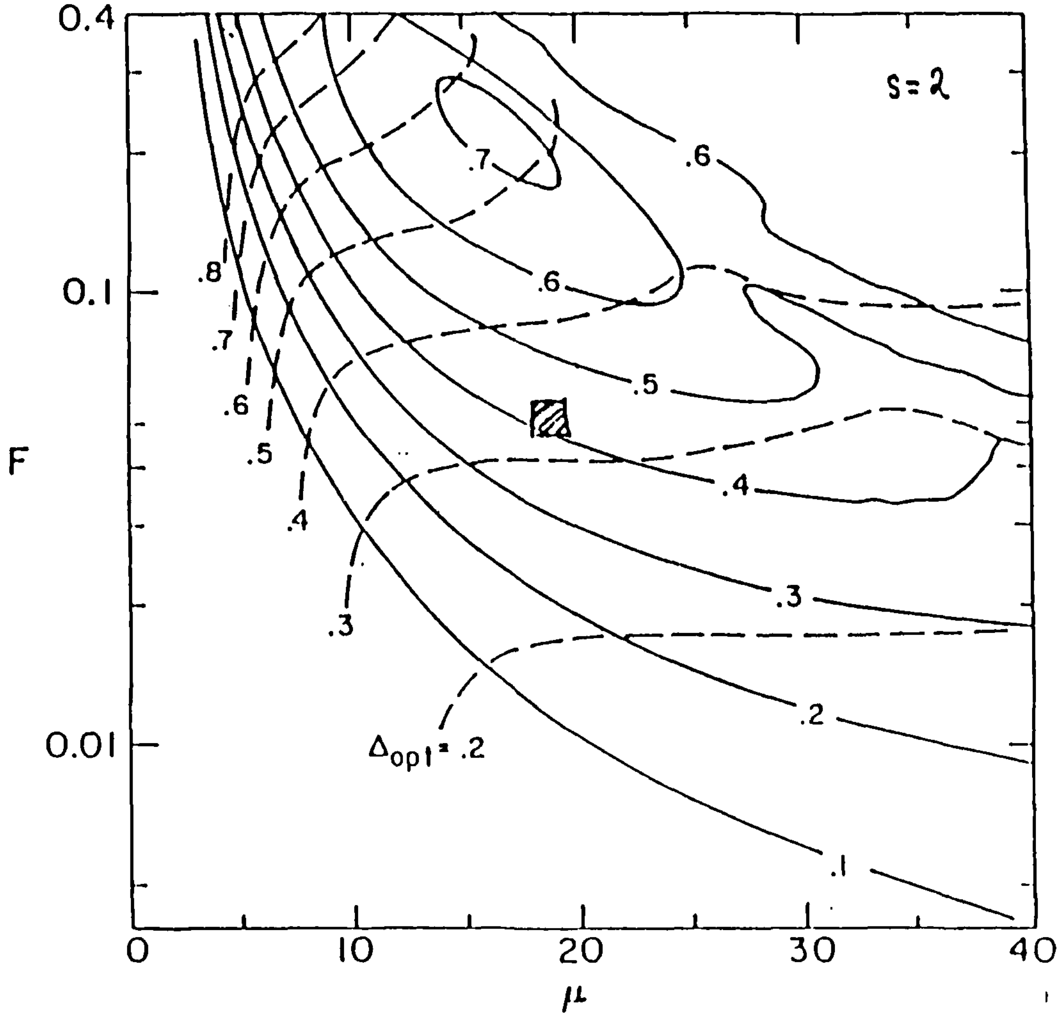
QUASI-OPTICAL RESONATOR CONFIGURATION
$\vec{E}_{rf}$
X
R_m
a_m
y
W_m
W_o
$\vec{B}_0$
E-BEAM
d
Spherical
Mirror
$g = 1 - \frac{d}{R_m}$
Diffraction
output coupling

Figure IV 1



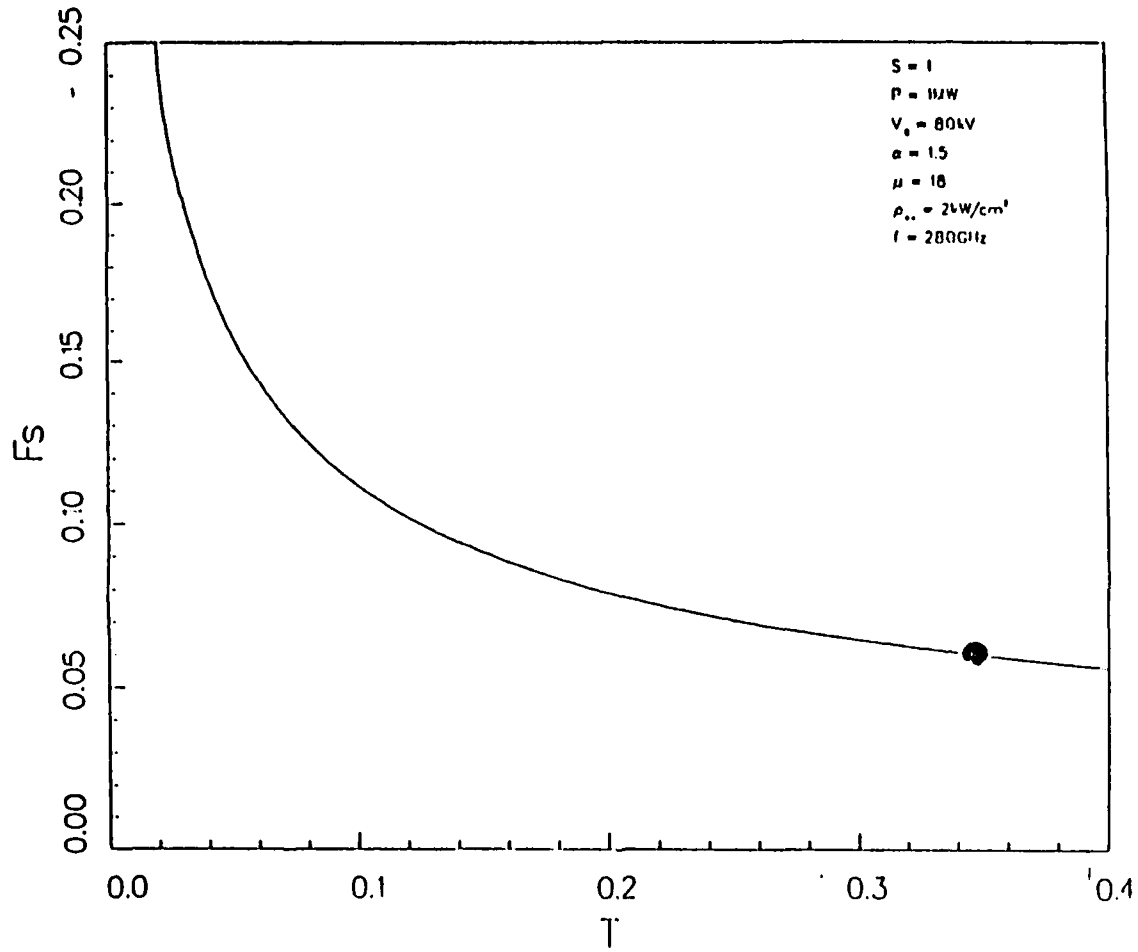
Danly + Temkin
MIT-PFC/JA-85-6

Figure IV 2



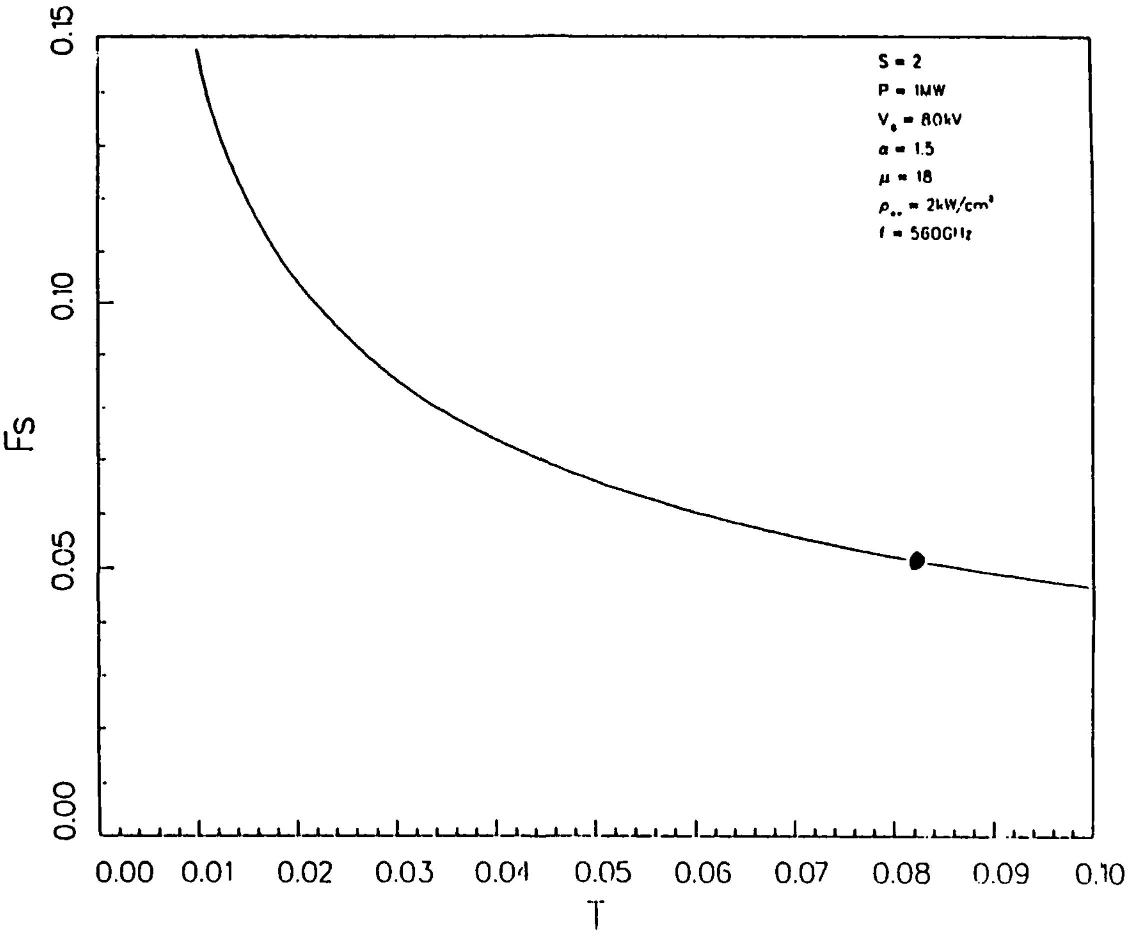
Danly & Temkin
MIT-PFC/JA-85-6

Figure IV 3



S = 1
P = 1MW
V_b = 80kV
α = 1.5
μ = 18
ρ_{ω} = 2kW/cm²
f = 280GHz
Fs
0.00
0.05
0.10
0.15
0.20
0.25
0.0
0.1
0.2
0.3
0.4
T

Figure IV 4



S = 2
P = 1MW
V = 80kV
α = 1.5
μ = 18
ρ = 2kW/cm
f = 560GHz
Fs
0.15
0.10
0.05
0.00
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
T

Figure IV 5

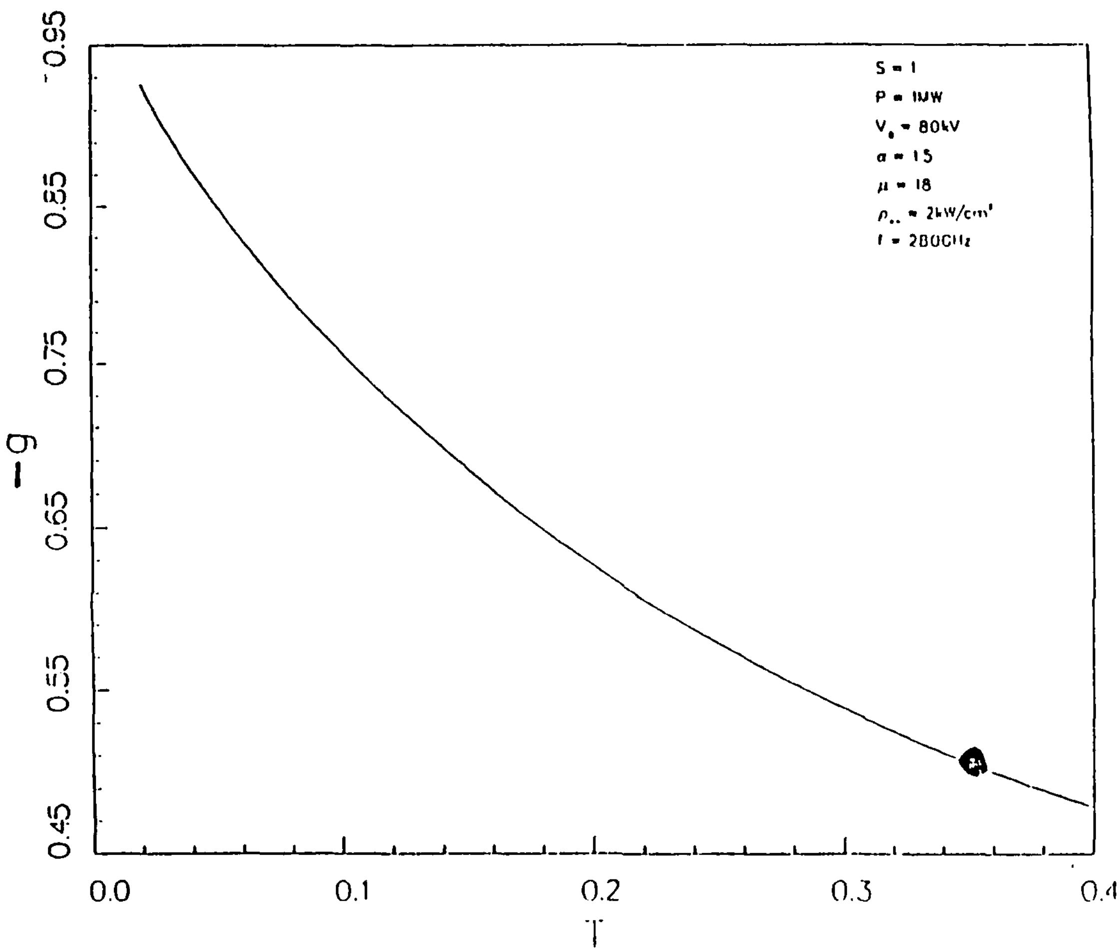


Figure IV 6

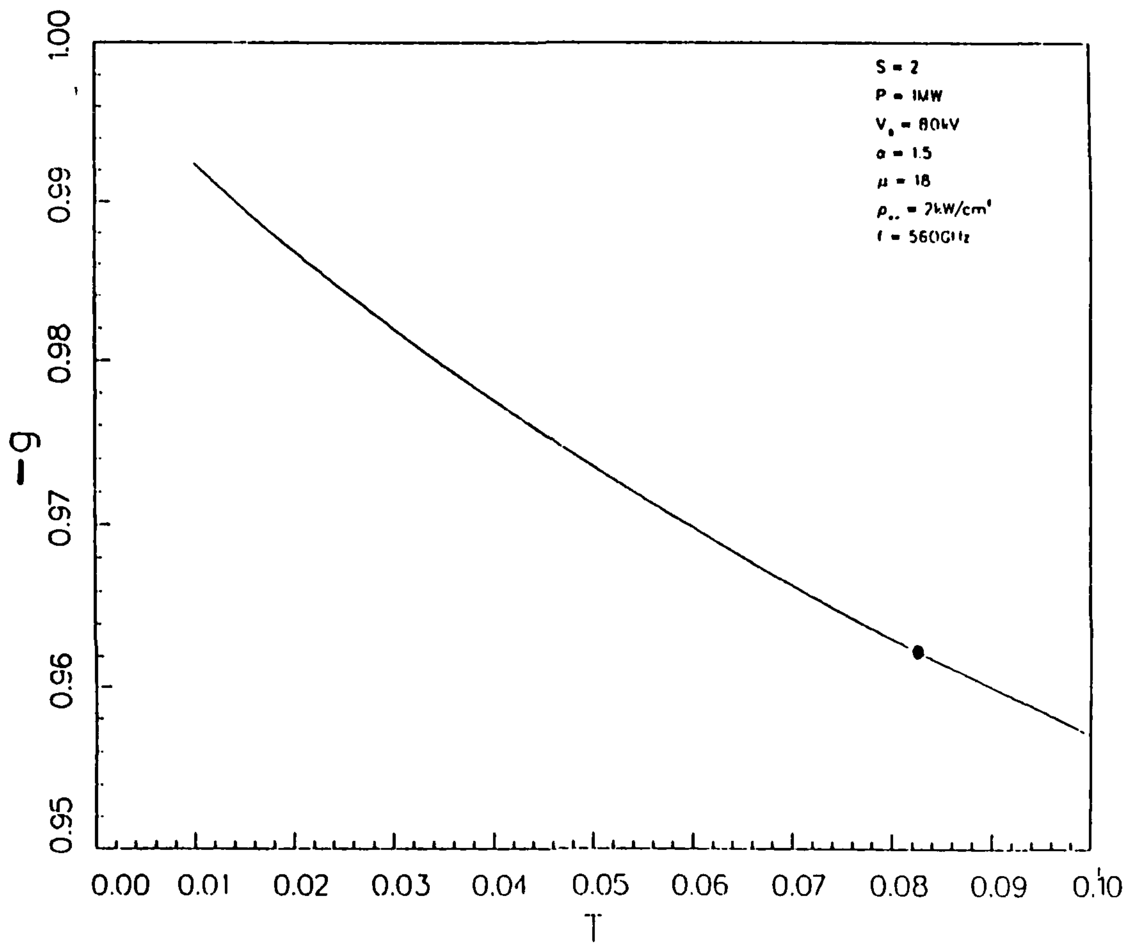

1.00
0.99
0.98
0.97
0.96
0.95
$-g$
S = 2
P = 1MW
V_b = 80kV
α = 1.5
μ = 18
ρ_{oh} = 2kW/cm²
f = 560GHz
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
T

Figure IV 7

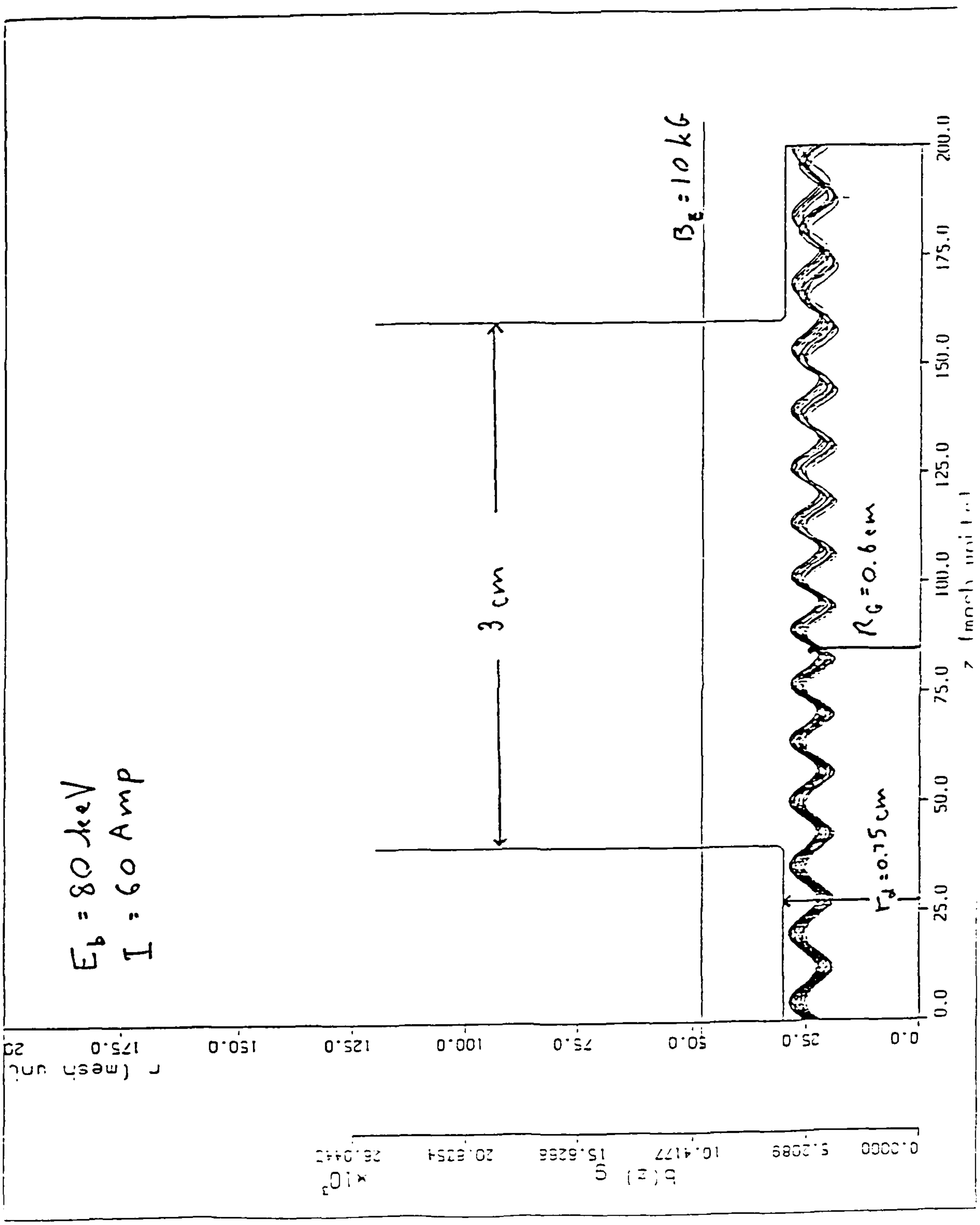

E_b = 80 keV
I = 60 Amp
B_z = 10 kG
3 cm
R_G = 0.6 cm
r_d = 0.75 cm
0.0
25.0
50.0
75.0
100.0
125.0
150.0
175.0
200.0
r (mesh uni
b(z) G
x10^3
0.0000
5.2089
10.4177
15.6266
20.8354
26.0442

Figure IV 8

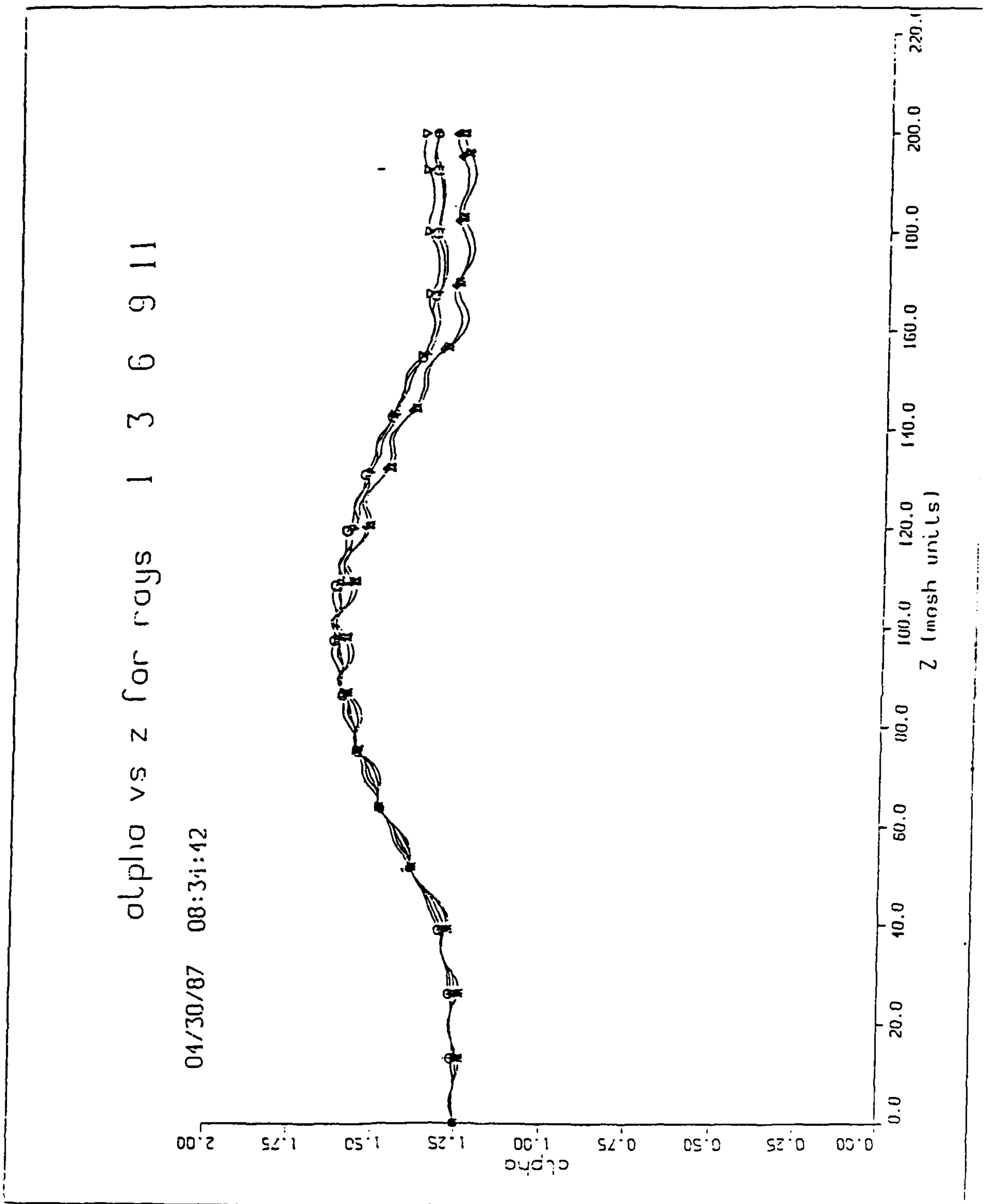
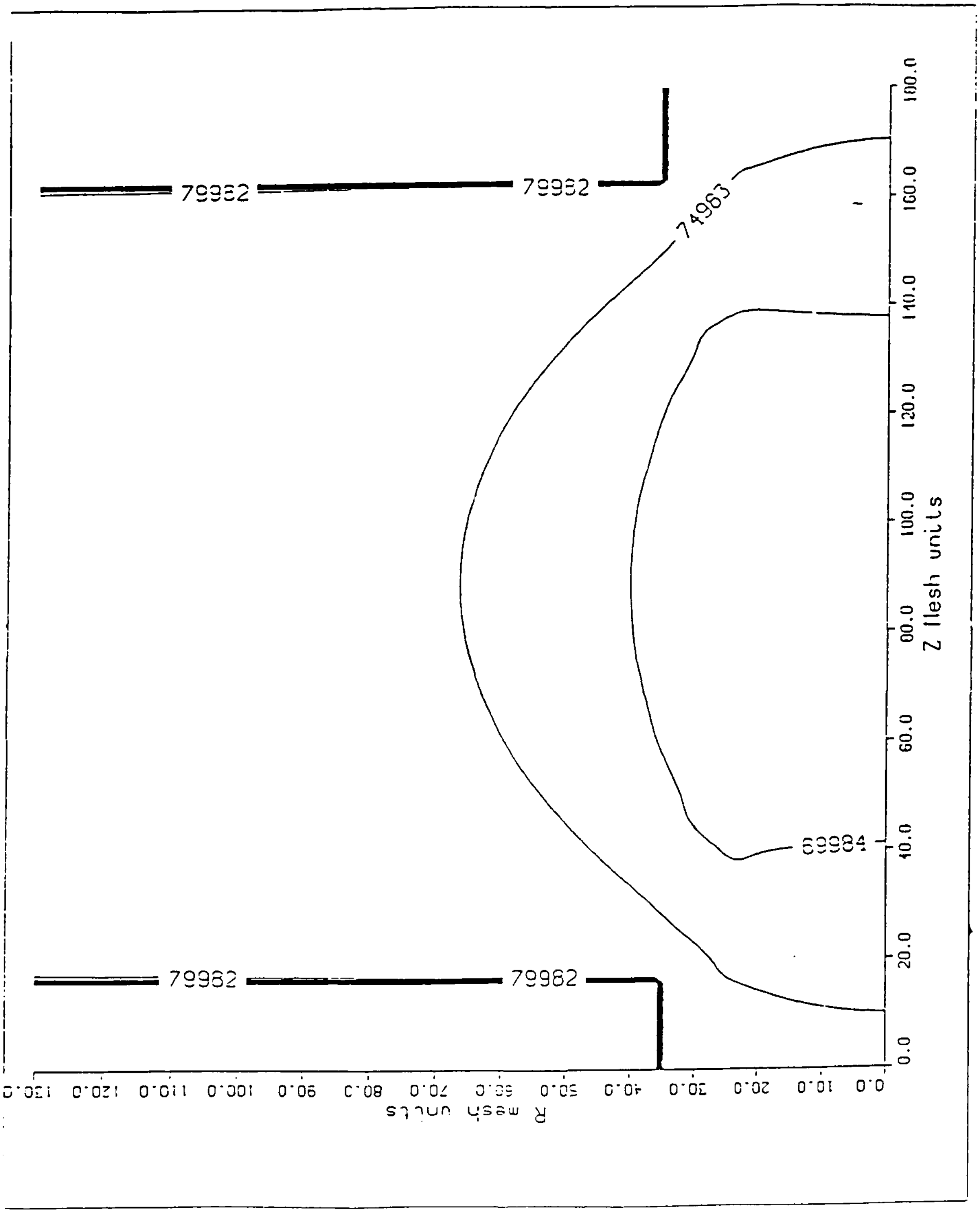

alpha vs z for rays 1 3 6 9 11
04/30/87 08:31:42
alpha
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
Z (mesh units)
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
200.0
220.0

Figure IV 9



79982
79982
79982
79982
74983
69984
Z Mesh units
R mesh units
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0

Figure IV 10

V. Experimental Program

In this section, we summarize the proposed experimental program. The section is divided up into three subsections concerning the past experiments, the present experiment, and the proposed future experiments.

A. Past Experiments

The experimental program on quasi-optical gyrotrons at the Naval Research Laboratory has proceeded very slowly because of problems with equipment and management. As discussed later on in this section, we believe these problems have been solved, and the laboratory has invested a considerable amount of its own resources in solving them.

Regarding the material problems, early on the strategy was to do the experiment with an electron gun designed and fabricated at NRL. This gun failed, meaning a considerable amount of time was lost. Also, the original quasi-optical magnet failed to operate reliably at the design fields. This particular magnet design also had inside thermal insulation which flaked off the inner surface and fell onto the gun, poisoning the cathode. To complicate matters further, when the magnet arrived, it was not tested during either the acceptance or guarantee period.

As the program was originally set up, a full time experimentalist operated under the direction of the principal investigator, Dr. Michael Read. An early difficulty was the rapid turnover of the full time experimentalist associated with the project. In the first four years, the experimentalist shifted from David Kim, to S. Y. Park to Thomas Hargreaves. The experiment done in September of 1986 was done by Michael Read after no other experimentalist could be recruited. Despite the difficulties, however, two experiments were done, a small mirror experiment by Thomas Hargreaves[5] in October 1984, and a large mirror experiment by Michael Read[6] in September 1986.

A schematic of the small mirror experiment is shown in Fig. V 1, and the output structure used is shown in Fig. V 2. The electron gun used was a Varian VUW-8010 (Seftor) electron gun which has been the main workhorse up to now in our gyrotron experiments. The output radiation is extracted from one of the mirrors through a coupling slot and travels over a matching cone so it fills the waveguide. The electric field is polarized as a standing TE_{1n} mode, so that in the output waveguide, these would be the modes formed. We have found that diffraction coupling around the edge of the mirror is the most effective output scheme. An alternate scheme, coupling through a small hole in the center, was tested experimentally by S. Y. Park. It was found to destroy the transverse mode selectivity of the resonator

and greatly reduce the power and efficiency of the device. Theory now supports this interpretation.

The waveguide leads to the calorimeter where the power is measured. The mirror spacing is small enough and the mode spectrum sparse enough that the system was never observed to multi-mode. In Fig. V 3 is shown the measured frequency as a function of magnetic field. As is apparent, the system is magnetically tunable from about 102-116 GHz. The cases where different modes exist at the same field is not multimoding; rather, it represents single modes at the same magnetic field, but different current, voltage or field taper. In Figs. V 4 and 5 are shown the power and efficiency as a function of current at different fields. This highest measured efficiency is about 11%, and the highest power shown is about 70 kW. Actually, the highest power (not shown in Fig. V 4) was 80 kW at a field of 41.2 kG.

A schematic of the large mirror experiment is shown in Fig. V 6. In that experiment, no prebunching cavity was used, but the mirrors were 81 cm apart. Because the mirrors are not deep inside the magnet, as was the case in the small mirror experiment, one has the choice of using a Cassegrain output system shown in Fig. V 7. Here the radiation diffracted around the edge of the mirror is reflected off a large elliptical ring mirror outside, and then refocused onto a convex mirror to form a Gaussian beam.

As expected, the large resonator configuration did show a tendency to multimode. Fig. IV 8 shows the mode spectrum at a time of 7 microseconds into the pulse, showing clearly the presence of two longitudinal modes simultaneously. This multimoding apparently degraded both the power and efficiency as one might expect. Figures IV 9 and 10 show the power and efficiency of the device as a function of current and magnetic field taper. The highest efficiency now is about 6%.

To summarize, NRL did two quasi-optical gyrotron experiments, one in October 1984, and one in September 1986, which were the first quasi-optical gyrotron experiments ever performed. These were done with a Seftor electron gun at a voltage of 60 kV and a current of up to 17 Amps. The power was extracted from one side of the cavity, and the maximum power was 80 kW, and the maximum efficiency was 11%.

B. Present Experiments

One of the problems which has held up the progress of the quasi-optical gyrotron project in the past has been the cross bore magnet. The original magnet manufactured by the IGC corporation was out for redesign and repairs almost constantly from October 1984 to August 1986. Around November 1985, it appeared entirely possible that it would never be available. The

laboratory then ordered, out of Plasma Physics Division ACP funds, a new cross bore magnet manufactured by the AMI corporation. This company has built many of our high field magnets and their products have been reliable in the past. This magnet arrived in January 1986, has been tested and works well. (Notice that the time to order the magnet and have it built, was less than the time to have the original magnet repaired.) Another difficulty in the project has proven to be the management structure. On October 10, 1986, the original management was replaced and a new management structure initiated. This has brought the group together, and has led to the return of Tom Hargreaves for a year, which has enabled us to do an experiment this year.

This year, an experiment on the small mirror configuration will be done with the aim of getting a large amount of data on several cavity configurations. Toward this end, a mirror holder has been designed and built which will allow adjustments of the mirror separation and orientation without breaking vacuum. The drawing of the mirror holder is shown in Fig. V 11. This holder will allow for multi-dimensional parameter studies to be made in one configuration. Other configurations can be studied by changing the mirrors. If all parts come in as scheduled and fit together as planned, the experiment should be underway in June 1987.

The aim of this is to experimentally examine the wave particle interaction for the case where multi-moding is not a problem. We hope to achieve power in excess of 100 kW, and to determine experimentally the maximum output coupling, as well as the issue of frequency tuning with beam voltage, magnetic field and mirror separation. In this new experiment, power is extracted symmetrically from both sides of the resonator. Theory predicts that this is the optimum extraction technique. Most of all, as this experiment has been designed and planned, we will have time to thoroughly examine these issues experimentally.

C. Future Experiments

For the purpose of this paper, the future experiment means those experiments taking place after January 1988 when the present small cavity, Seftor gun experiments conclude. In reaching for the megawatt power regime, a long-standing difficulty has been that of getting an electron gun at the appropriate power level. It was initially expected that a 4 MW electron gun would be fabricated at NRL. An 80 kV gun was designed and fabricated, but it failed to operate above 40 kV. To solve this problem, we have purchased, with our own research funds, a Varian VUW-8144 electron gun. A schematic of this gun is shown in Fig. V 12. This gun operates at a voltage of 80 kV

and at a current of up to 50 A. It has been the main stay of the MIT cavity gyrotron program. (We call it the MIT gun.) This gun should represent the solution to all of our major equipment problems for at least the next two years; that is, until the arrival of a high field cross bore magnet, and a sheet beam electron gun designed for the quasi-optical gyrotron.

The goal of the proposed NRL program is to do the research and development necessary for the industrial production of unit tubes for ECRH on CIT. NRL proposes to do the research at short pulse (that is 25 microseconds or less), so for timely utilization on CIT, and also on Alcator C Mod, industrial development of the specifically long pulse components (the collector, window, power supply and modulator) would have to proceed in parallel. Many of these components could fit whatever tube that would be used to heat CIT and Alcator C Mod, and are not specific to the quasi-optical gyrotron.

The proposed NRL program will be a double pronged effort which fully utilizes the quasi-optical magnets we have. We propose the setting up of two laboratories - one to examine the potential of the quasi-optical gyrotron at the cyclotron frequency and one to examine its potential at the harmonic. Each laboratory will be under the direction of a Ph.D scientist, each will have a technician, but they will share an engineer. The time of the proposed program is four years. At the end of that

time, the crucial issues will be resolved and CW relevant demonstration tubes at the megawatt level will be produced at 240 GHz at both the fundamental and the harmonic. In the four year proposed program, there will not be a demonstration tube at 480 GHz. This would be done in a follow on program at the harmonic, utilizing the high field magnet and the sheet beam gun. If the four year program is successful, especially the harmonic portion of it, the follow-on tube at 480 GHz should be relatively straightforward. Finally, we note that the frequencies at which the NRL program will operate, 120, 240, and 480 are slightly less than the frequencies required for CIT. This is to be consistent with existing equipment. We do not expect that an industrially produced tube, at roughly 10%-15% higher frequency, will be significantly different.

The new phase of the experimental program at the fundamental (120 GHz) will begin around February of 1988 when the MIT gun arrives. This will allow us, for the first time, to experimentally investivate the high power potential of the quasi-optical gyrotron. The first experiment will be done on the small cavity configuration so as to investigate high power issues without the added complication of mode competition. We expect to be able to generate power in the range of half a megawatt, and to experimentally pin down the issues of voltage and magnetic field tunability, as well as the maximum allowed output coupling. We

expect to achieve power in the half megawatt range, by about the summer of 1988. Right after that, we ill do a series of high power experiments with the MIT gun and a large mirror configuration. Because of the problem with multi-moding, we expect less power than with the small mirror configuration. By late fall of 1988, or early winter of 1989, we expect to have achieved power in the quarter to third megawatt range.

With the quasi-optical gyrotron, we expect to first achieve high power and high efficiency when we utilize a prebunching system. As we have discussed, the prebunching not only allows mode control, but also enchances the efficiency of the tube. By about the spring of 1989, we expect to have designed a prebunching system which will go on the large mirror quasi-optical gyrotron. It is this experiment which will efficiently produce high power, 120 GHz radiation at the megawatt level. By late fall of 1989, or early winter of 1990, we will have achieved a megawatt level, CW relevant source at 25%-30% efficiency. Also, we will have examined the voltage and magnetic field tunability, and experimentally determined the output coupling at which the tube can operate. The expectation will be to achieve 3%-5% voltage, and 20%-30% magnetic field tunability.

Another portion of the high efficiency, high power experiment will be the analysis of the spent beam after the interaction. While we do not intend to build a depressed collector ourselves

as part of the program, a detailed knowledge of the energy distribution of the spent beam will allow industry to design a high efficiency depressed collector. The quasi-optical gyrotron is very well matched to a depressed collector, because the radiation and beam are extracted in different places. A very large collector (i.e., trash can size) can be put on top, and it will not interfere at all with the radiation output. With the use of a depressed collector, the power supply can be made smaller, with the subsequent reduction in cost.

To proceed further with studies at the cyclotron frequency, a high field cross bore magnet would be required. We have made some initial inquiries to magnet companies, and have found that a 100 kG cross bore magnet, of the proper dimension could be built in about nine months for about $250k. This magnet would have to be ordered, and in our program plan, it would arrive around January of 1990. The studies at the fundamental frequency would then continue on the high field magnet. Another constraint is the electron beam configuration. The MIT gun produces an annular beam, and as the frequency of the gyrotron increases, the radiation waist decreases faster than the beam radius decreases by magnetic compression. Thus at some point, the annulus of the beam is just too large to intercept much of the radiation in the cavity. We have found that at 120 GHz, the MIT gun is well matched to the radiation waist. At 240 GHz, there will be a

significant loss of total efficiency, and at 480 GHz, it would not be possible to use the MIT gun with any kind of acceptable efficiency. To proceed with the program then, an important part is the design of a sheet beam electron gun. Such a beam is much better matched to the quasi-optical configuration, and the original paper spoke about using a sheet beam gun.[1] Furthermore, in planar configuration, the space charge limiting current is expressed as a current per unit length rather than as a total current. Therefore, by making a long enough sheet, very large currents could be propagated. A preliminary study of the design considerations for a sheet beam using a planar analog of a MIG gun has been worked out[7] and will be used as the starting point for our design. During the first year of the program, a design will be worked out for a 6 MW sheet beam electron gun. This gun will then be ordered from industry and we expect it to arrive around early winter of 1990. At this point, the experimental program at the cyclotron frequency will continue with the high field magnet and the sheet beam electron gun.

With the sheet beam gun and high field magnet, we would go through essentially the same steps at 240 GHz as we did at 120 GHz. By about early summer of 1990, we would hope to have small mirror data at a power level in excess of half a megawatt. Also, the tunability with both voltage and magnetic field would be experimentally determined. By about early fall of 1990, we

expect to have data on the large mirror configuration, although at a lower power, about one third to one half a megawatt. Finally, we would do a large mirror experiment with a prebunching cavity to achieve power of over one megawatt in a CW relevant configuration by late fall, 1991. The tunability with voltage and magnetic field would be experimentally determined.

We now discuss the portion of the proposed program at the cyclotron harmonic. These experiments would be at a frequency of about 240 GHz. It would be very important to purchase diagnostic equipment at this frequency very early on. The most difficult portion of this research area would undoubtedly be suppression of the fundamental. Here quasi-optical gyrotrons could have a real advantage over cavity gyrotrons because optical techniques could be used. The simplest optical technique involves exploiting the smaller spot size at higher frequency to lower the starting current of the harmonic. While this does discriminate against the fundamental, it forces the operation into a fairly low efficiency regime. Other optical techniques involve the use of grating mirrors which can reflect the fundamental to a different location out of the cavity. An early experiment would be to produce the second harmonic radiation at 240 GHz by using optical techniques to suppress the fundamental. This would be done in a small cavity configuration so as to eliminate the complications of multi-moding. We would expect to have the results here by

about late fall, 1988. Since one is forced into a fairly narrow corner of parameter space, the power and efficiency would be low, about 25-50 kW and about 3%-8% respectively. These experiments would be done with the Seftor gun so that the power would not be in the megawatt range. However, the Seftor gun does produce a very tightly focused beam so that there is no problem of the beam not overlaping the radiation waist.

To realize the full potential of the quasi-optical gyrotron at the harmonic, a prebunching system would have to be utilized not only for mode control and efficiency enhancement, but also expand the region of parameter space allowing suppression of the fundamental. One way to do this is to design into the feedback system a filter so that only the harmonic is fed into the prebunching cavity. By early summer of 1989, we would have such a prebunching system at the harmonic. By late fall of 1989 we would have a data set at 240 GHz on a second harmonic experiment which utilized a prebunching system. We would expect to achieve power between 50 and 150 kW and efficiencies of between about 8% and 25%. Also, we would experimentally determine the tuning with voltage and magnetic field, as well as the maximum output coupling allowed. These experiments would still be done on the small mirror configuration, however, because we feel that there are still physics issues to settle regarding suppression of the fundamental, and these can best be settled if one does not have the complication of multi-mode excitation.

At this point, the 6 MW gun will arrive, and the MIT gun will become available for studies of harmonic operation at high power. Since the beam is not well matched to the radiation waist at 240 GHz, there would be some degradation of efficiency. However the program plan would be to redo both small mirror harmonic operation experiments at high power. Because of the experience up to this point, these would go quickly. By late spring of 1989, we would do single cavity experiments at high power and achieve power at the 100 kW level; by early fall, we would have a data set on the double cavity experiments achieving a power level of about 300-400 kW (corresponding to roughly 500 -700 kW with the sheet beam electron gun). In the double cavity experiments, the tuning with magnetic field and voltage would be experimentally determined. During the final year and a half of the project, a large cavity, CW relevant second harmonic experiment would be set up to produce power at 300-500 kW level. Here, frequency tuning with voltage and magnetic field would be determined experimentally.

Finally, during this last year and a half, a design would be done for a second harmonic experiment at 480 GHz utilizing the high field magnet and sheet beam electron gun. As part of this study, the necessary diagnostics at 480 GHz to be purchased or developed would be identified. The actual experiment would be done in a follow-on program for a fifth and perhaps a sixth year.

THE NRL QUASI-OPTICAL GYROTRON

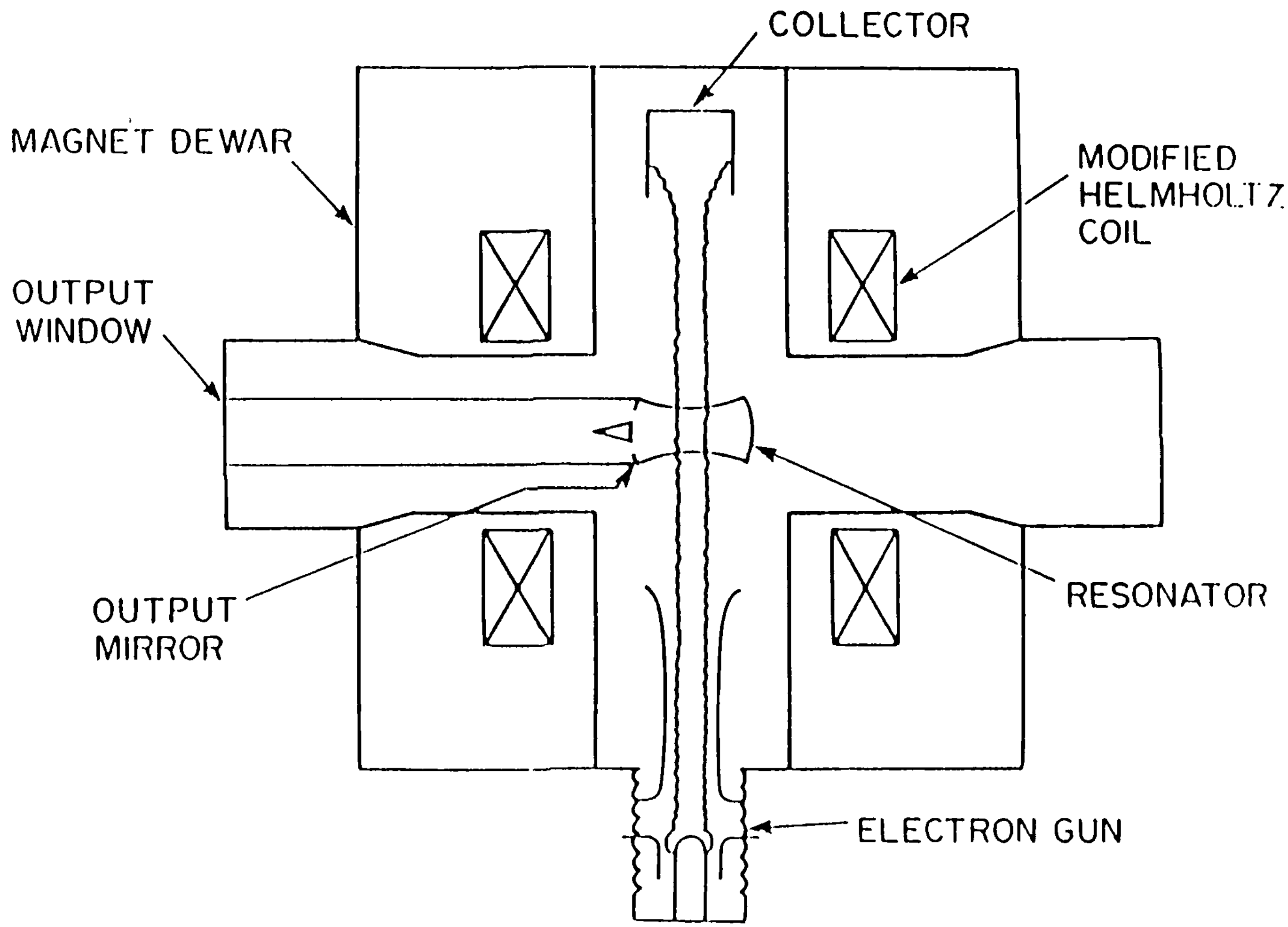


Figure V 1

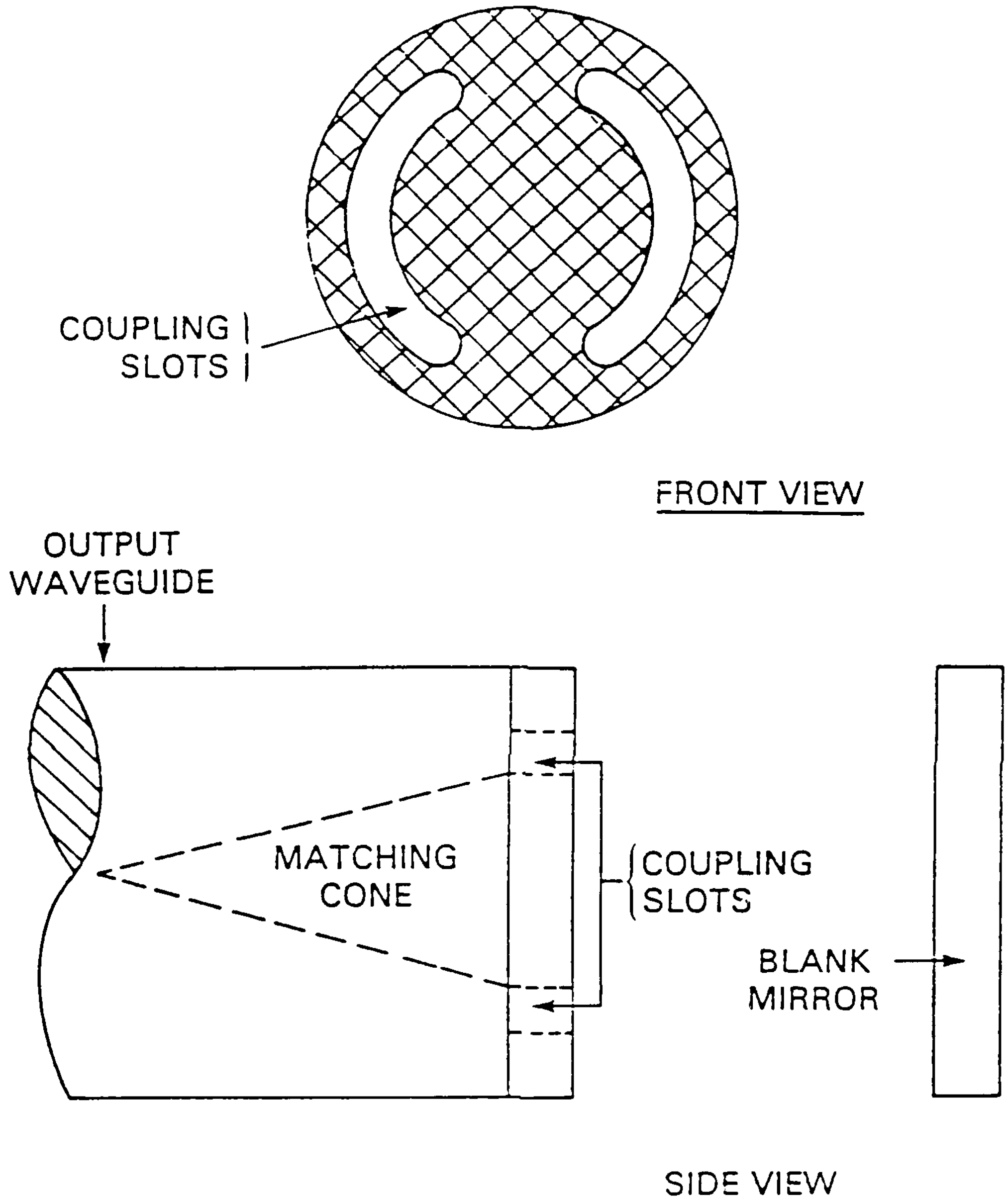
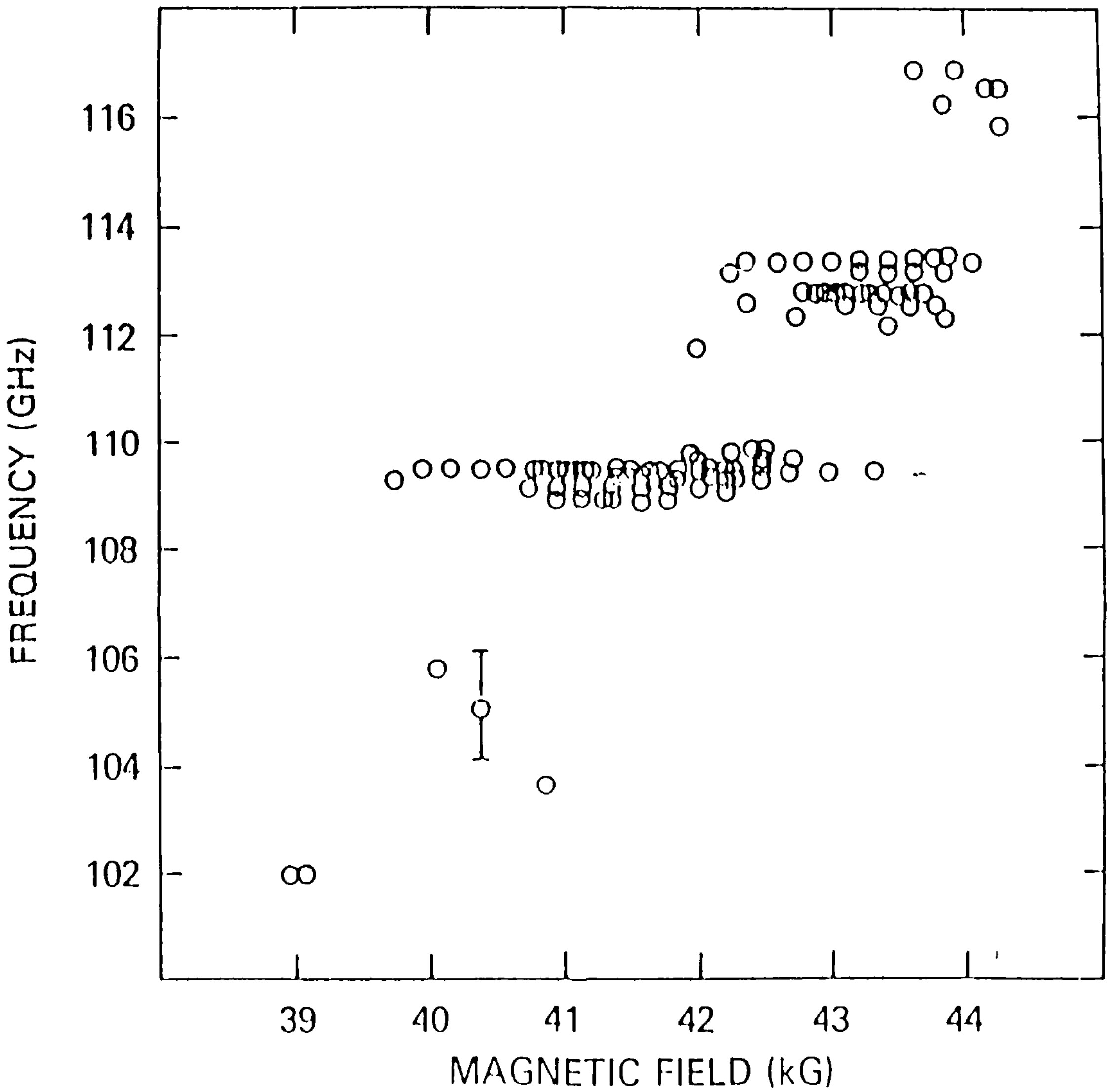
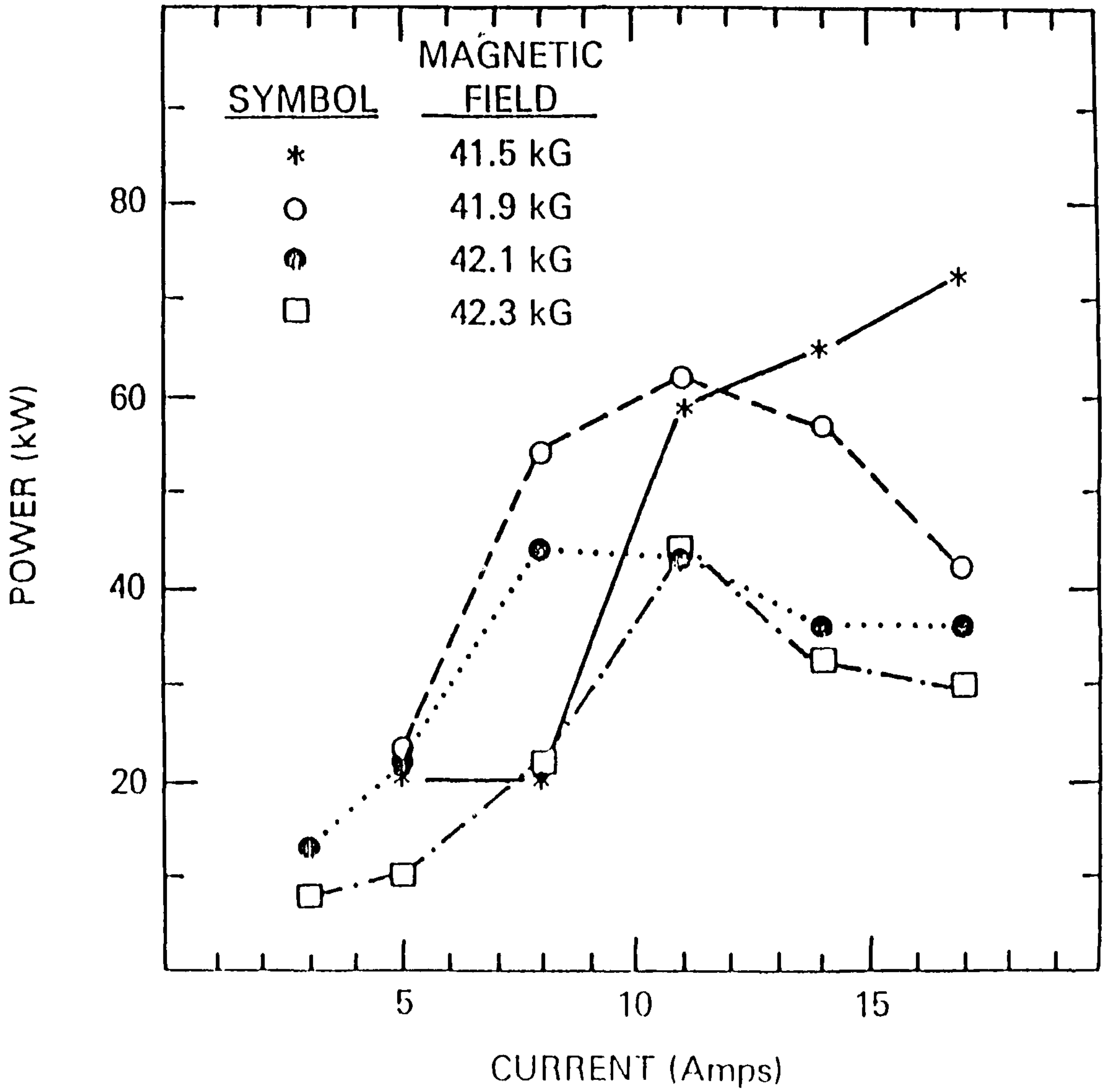

COUPLING
SLOTS
FRONT VIEW
OUTPUT
WAVEGUIDE
MATCHING
CONE
COUPLING
SLOTS
BLANK
MIRROR
SIDE VIEW

Figure V 2



116
114
112
110
108
106
104
102
FREQUENCY (GHz)
39
40
41
42
43
44
MAGNETIC FIELD (kG)

Figure V 3



SYMBOL
MAGNETIC FIELD
* 41.5 kG
○ 41.9 kG
◐ 42.1 kG
□ 42.3 kG
80
60
40
20
POWER (kW)
5
10
15
CURRENT (Amps)

Figure V 4

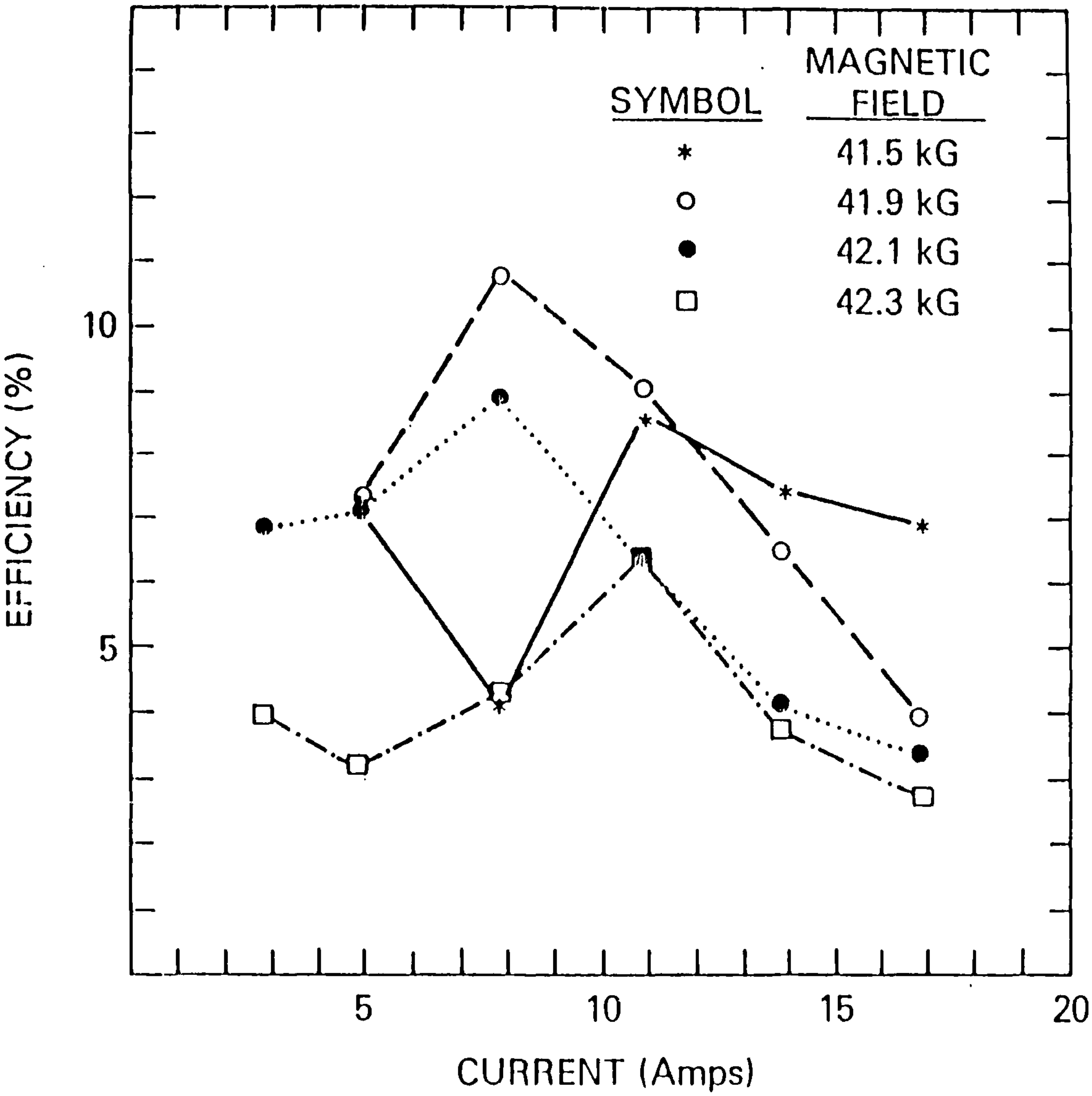

MAGNETIC
SYMBOL
FIELD
41.5 kG
41.9 kG
42.1 kG
42.3 kG
10
5
EFFICIENCY (%)
5
10
15
20
CURRENT (Amps)

Figure V 5

120 GHz QUASI-OPTICAL GYROTRON

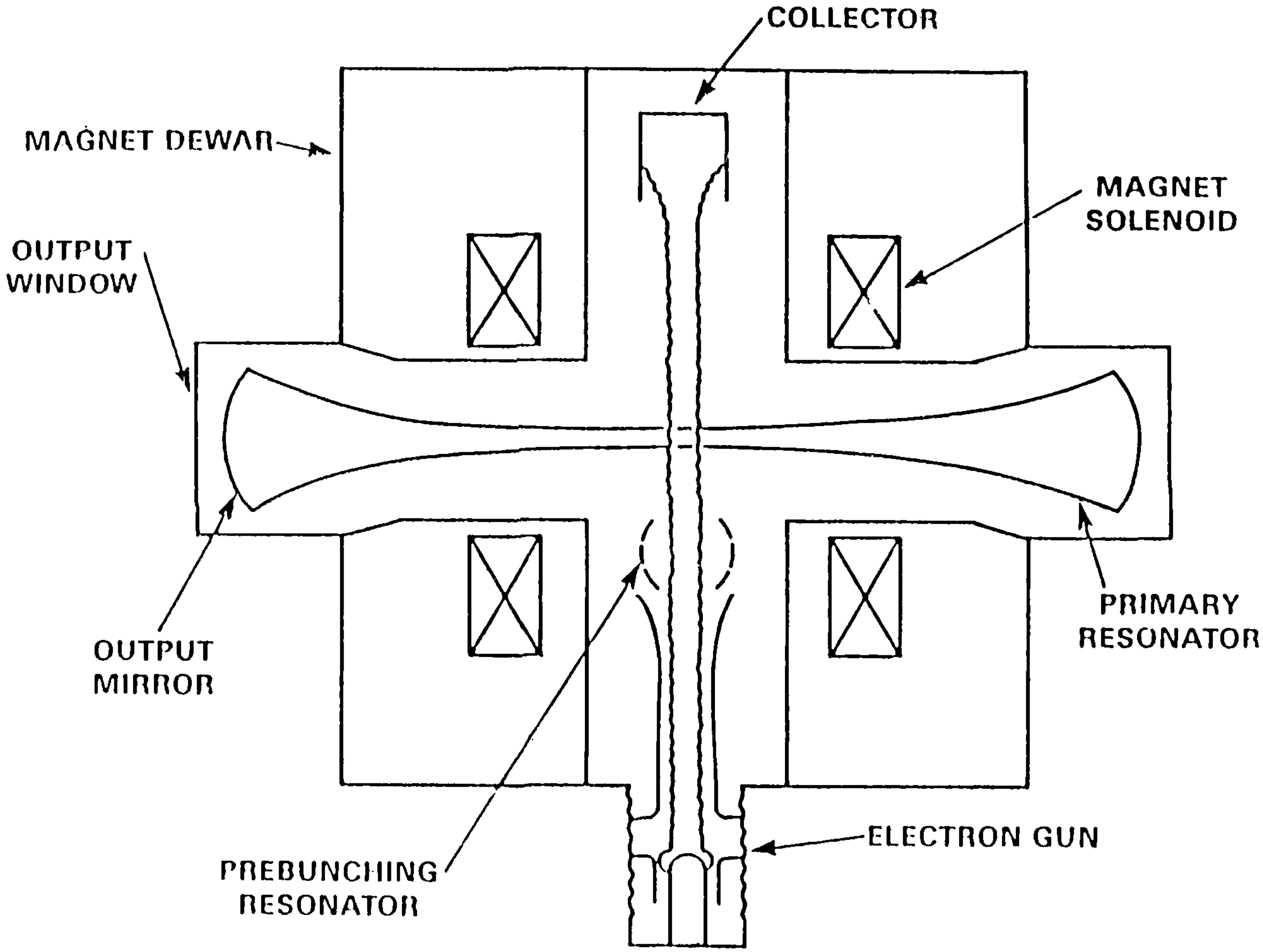
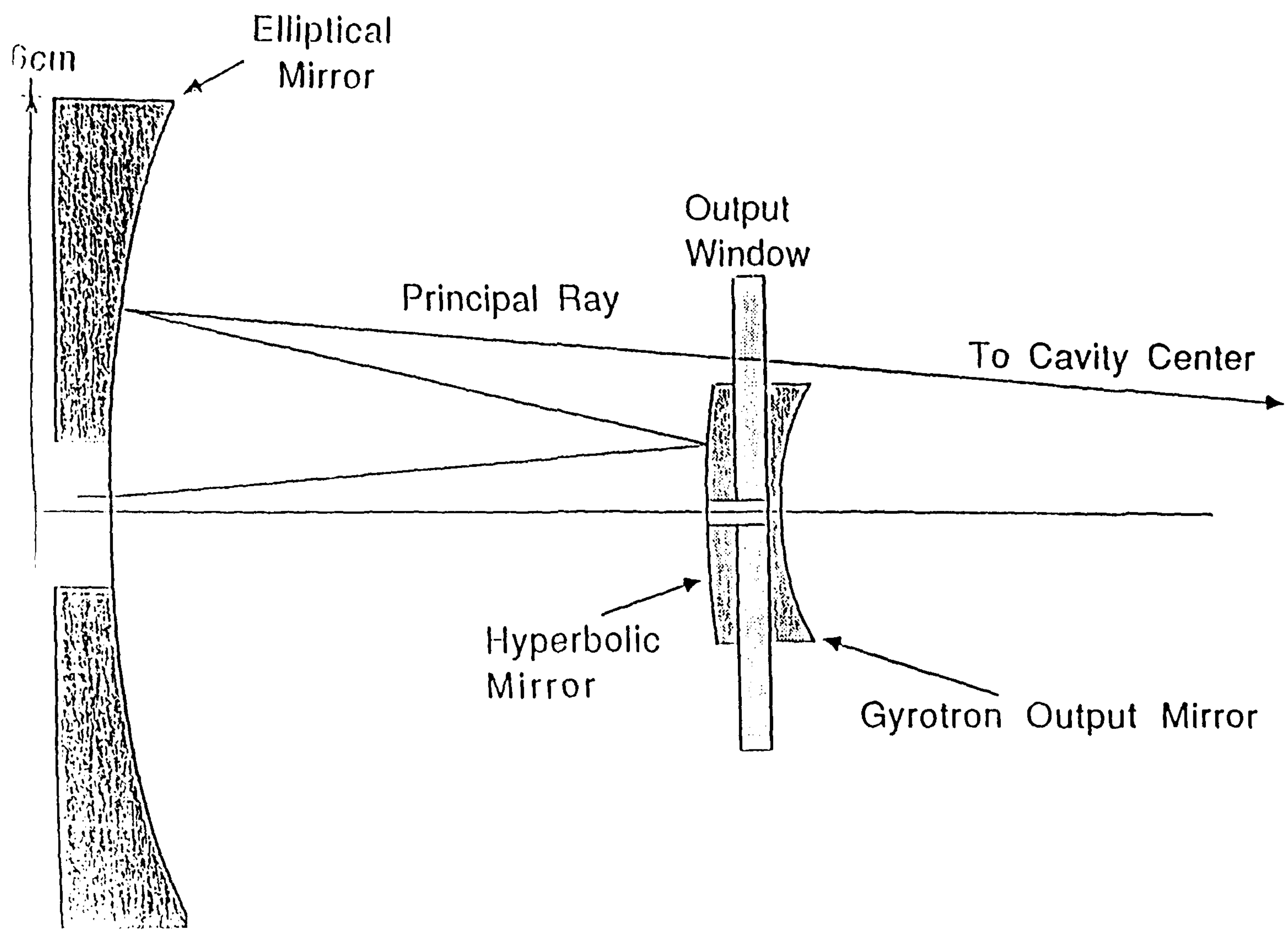


Figure V 6



6cm
Elliptical
Mirror
Principal Ray
Output
Window
To Cavity Center
Hyperbolic
Mirror
Gyrotron Output Mirror

Figure V 7

LARGE MIRROR Q.O. GYROTRON
FREQUENCY SPECTRUM

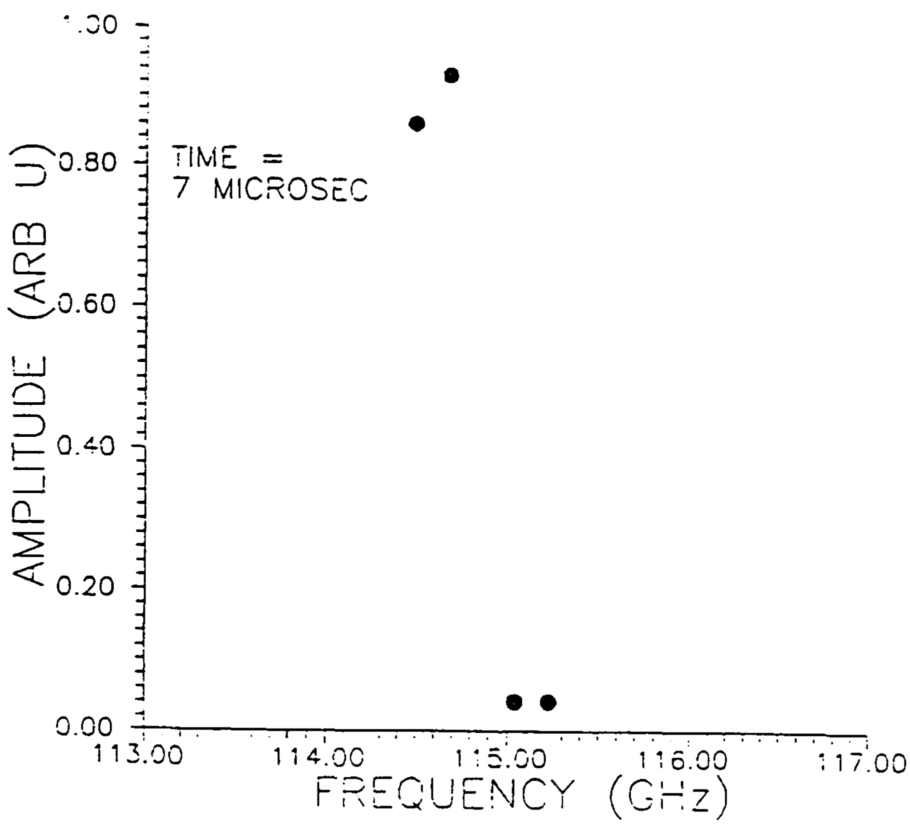


Figure V 8

LARGE MIRROR Q.O. GYROTRON
POWER vs BEAM CURRENT

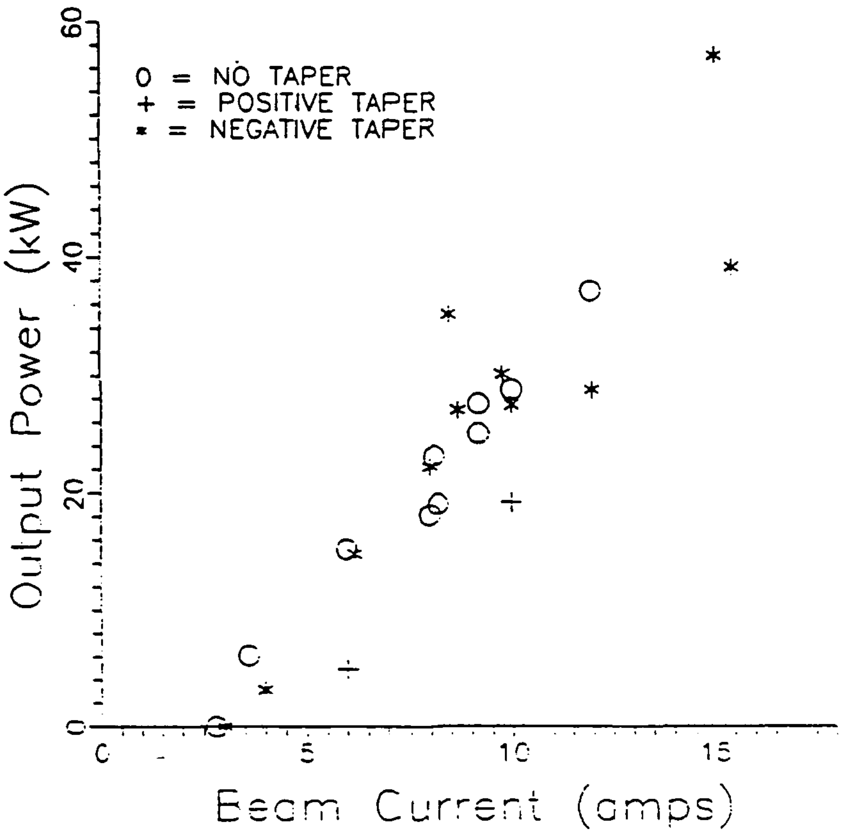


Figure V 9

LARGE MIRROR Q.O. GYROTRON
EFFICIENCY vs BEAM CURRENT

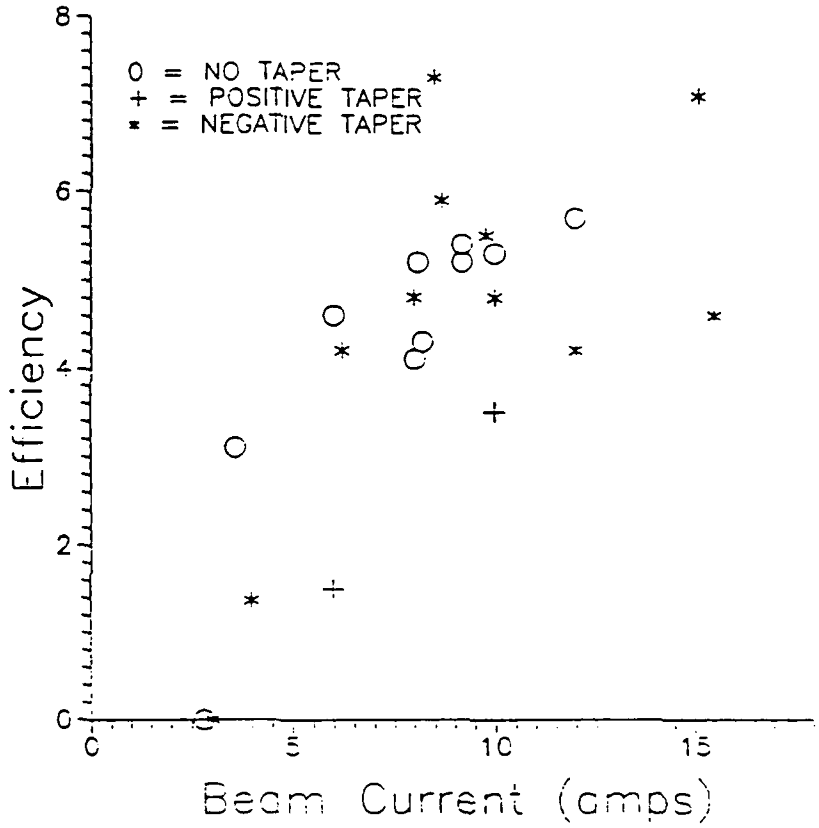


Figure V 10

Quasi-Optical Gyrotron Adjustable Mirror Holder

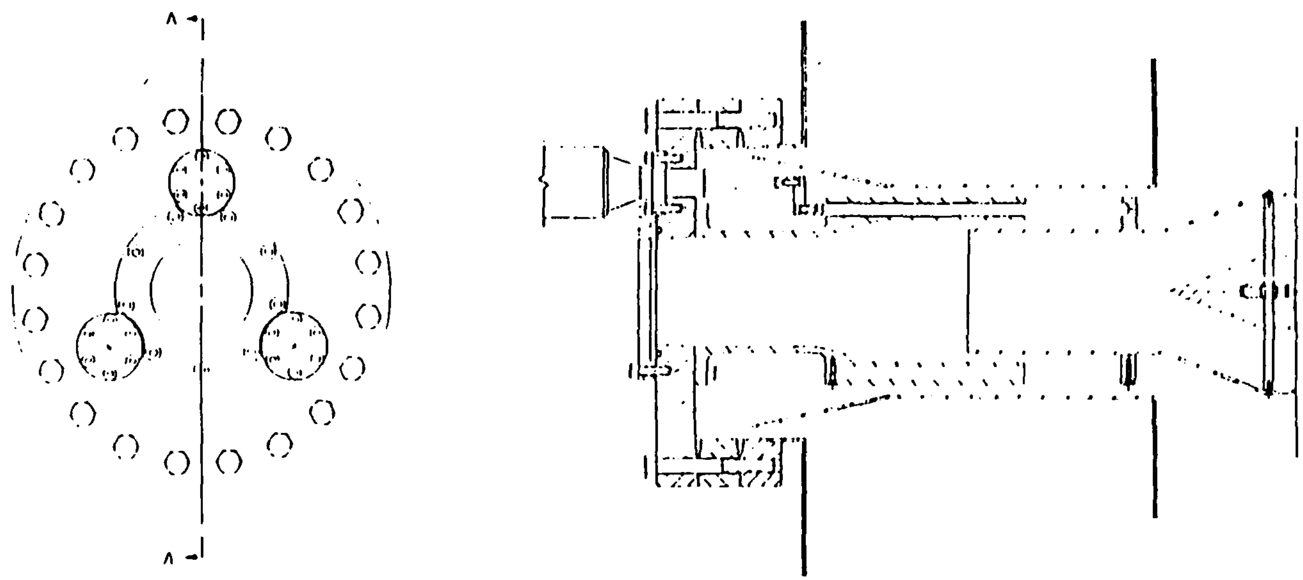


Figure V 11

VARIAN VUW-8144 (MIT) ELECTRON GUN

80 kV 50 A

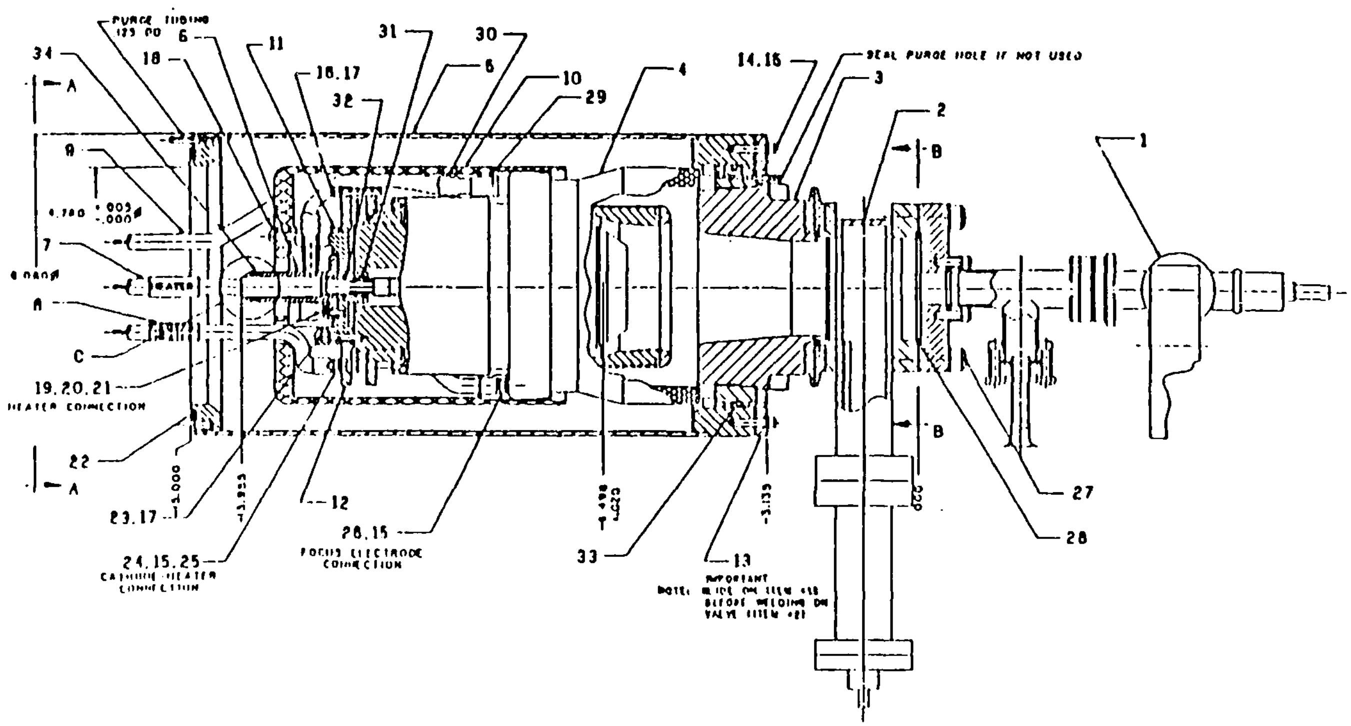


Figure V 12

VI. Program Plan and Summary

In this section we propose a program plan whose aim is to settle the physics issues regarding the quasi-optical gyrotron and to achieve an order of magnitude increase in the performance of experimental devices. The period of time of the proposed program is four years. During this time, two courses will be followed which we believe have a high probability of leading to industrial development of megawatt level tubes for use on CIT at a frequency of 280 GHz. This involves the setting up of two quasi-optical gyrotron laboratories, one dedicated to studies at the fundamental frequency, and one dedicated to studies at the second harmonic. In the four year program proposed, there would be no experimental work at 500 GHz; rather, this would be part of a follow on program if operation at the harmonic proves to be a feasible way to generate high power radiation at 240 GHz. It seems to us that the quasi-optical gyrotron offers the only hope of achieving 560 GHz with a low voltage (80 kV) beam with CW relevant ohmic heating loads..

The program at the Naval Research Laboratory will ultimately operate at three frequency ranges: 100-120, 200-240, and 400-500 GHz. Somewhat higher frequencies are achievable with existing magnet technology; however, to be consistent with equipment at NRL, the foregoing frequencies would be used in our research

program. Industrial development should focus on 140, 280 and 560 GHz.

There are 2 major pieces of capital equipment to be purchased: the 100 kG cross bore superconducting magnet, and a high power sheet beam electron gun. We have estimates from magnet companies that such a magnet could be built in about 9 months for about $250k. A 120 kG magnet with a 1" cross bore has been built by American Magnetics Inc. The design challenge would be to put in a cross bore with twice the diameter. (The existing magnet at 50 kG has a 4-1/4 inch cross bore). The second piece of large capital equipment required would be a sheet beam electron gun to better match the radiation profile in the quasi-optical gyrotron. For the initial high power experiment at 120 GHz, the MIT gun should be a good match. At 240 GHz, the MIT gun could still operate, but there would be a loss of efficiency because there would be a significant variation in the intensity of the radiation intercepting the electron beam. At 480 GHz, the experiment would not be possible without a sheet beam electron gun. Thus, such a gun would have to be developed as part of the program. An initial study of the design trade offs of such a gun has been done.[7] A final minor capital equipment purchase would be diagnostic equipment at 240 GHz. These are stock items, but are expensive due to the small size and precise tolerances. The cost of the necessary equipment is about $150k.

The issues to be examined experimentally in the program are enumerated in Fig. VI 1. Note that there is a progression from simple to difficult, and also that the issues are expressed as a pyramid: to resolve the lower items, the upper items must also be resolved. The milestones which the NRL program proposed to meet are enumerated in Figures VI 2 - VI 4 at the fundamental frequency, and in Figures VI 5 - VI 6 at the harmonic. There are specific milestones to address the tunability both on the slow time scale by varying the magnetic field, and also on a fast time scale by varying the voltage. Specifically, NRL will document the falloff in peak power as the device is operated through the tuning range and will investigate ways of reducing this falloff. Notice, also, that another milestone involves the analysis of the spent beam. This will produce a data base for the design of a high efficiency depressed collector. While a depressed collector would improve the performance of the quasi-optical gyrotron as regards efficiency, it is not essential for the operation of the tube. Thus, for CIT, the absence of a depressed collector would increase the overall cost of the rf system, however, the cost is fairly low to begin with. For ETR, where efficiency is crucial, a depressed collector would be a necessary part of the development. In Figures VI 7 - VI 12, the six items of importance for the tube are summarized, the frequency, unit power, output mode, schedule, cost, and applicability to ETR.

In order for the NRL program to lead to a tube useful in heating CIT, there would have to be early and co-ordinated industrial participation. This would have to involve the development of the long pulse components of the system, the modulator, collector, cooling system and window. For the Alcator C mod experiments, the pulse length is 20-100 msec; for CIT, the time is 3 sec. Another area for industrial participation is the design optimization of the cold bore superconducting magnet-electron gun configuration. This configuration appears to be necessary to the QO gyrotron but a significant departure from standard microwave tube manufacturing practices.

The Naval Research Laboratory proposes to set up two separate laboratories in existing space and with existing equipment to separately study the interaction at the fundamental frequency and its harmonic. Each laboratory would be under the direction of a Ph.D level experimental physicist. There would be two technicians and one engineer shared between the two laboratories. In addition to the two experimental physicists involved, there would be three other Ph.D level scientists involved in the program on about a one day per week basis. These are W. Manheimer (covered by laboratory indirect charges), A. Fliflet, and T. Hargreaves. Summaries of the costs of the program for four years, both capital and personnel are summarized in Figures VI 13 and VI 14. The costs are broken out on a per year basis in

Figure VI 15. In summary, the NRL paper is for a program costing approximately $981K per year for four years counting people, routine, and capital costs. Due to capital equipment procurement lead times, the per year cost increases to $1225K in the second year of the program and drops to $725K in the fourth year. At the end of four years, a quasi-optical gyrotron will have been built at 240 GHz, at a power of about 1 MW for transition to industry. In a follow on program, assuming that issues at the harmonic have been successfully addressed, a megawatt level tube at 480 GHz would be developed for transition to industry.

FUNDAMENTAL ISSUES TO BE ADDRESSED EXPERIMENTALLY 1988 - 1991

<u>Low Power</u>

- Experimental test of wave particle interaction as a function of cavity waist, cavity Q and beam current. Tunability with magnetic field and voltage.

<u>High Power</u>

- Mode selection with a dense spectrum i.e., how close can the mode separation be while maintaining mode control.
- Efficiency enhancement with prebunching.
- Examination of the spent electron beam.

<u>Second Harmonic</u>

- Suppression of fundamental.
- Operation at sufficiently low electric fields.

Figure VI 1

Milestones $\omega = \Omega_{ce}/\gamma$

1/88 Data set on small cavity, 2 or 3 different mirror sets.

Experimental issues:

- A) Mode change by beam Voltage,
- B) Tunability with magnetic field,
- C) Maximum allowed output coupling.

$P \approx 150$ kW, $\eta \approx 20\%$, $f \sim 120$ GHz

Where relevant, A, B and C will be done on all experiments.

6/88 Data set on small mirror. $P \approx 500$ kW, $\eta \approx 20\%$, $f \sim 120$ GHz

(1 MW CW Relevant for 120 GHz)

9/88 Design and order a 6 MW sheet beam electron gun for experiment.

9/88 Specify and order high field magnet.

Figure VI 2

11/88	Data set on large mirror. $P \approx 300$ kW, $\eta \approx 10\%$, $f \sim 120$ GHz
	(1 MW CW relevant experiment at 240 GHz)
3/89	Design of feedback system for gyroklystron oscillator experiment.
11/89	Data set on large mirror double cavity configuration.
	$P \approx 1$ MW, $\eta \approx 30\%$, $f \approx 120$ GHz
11/89	Analysis of spent beam for designing a depressed collector.
1/90	High field magnet arrives and sheet beam gun arrives.
	$\omega = \Omega_{ce}$

Figure VI 3

5/90	Data set - small mirrors.	$P \approx 500$ kW, $\eta \approx 20\%$, $f \approx 240$ GHz
9/90	Large mirror data set.	$P \approx 300$ kW, $\eta \approx 10\%$, $f \sim 240$ GHz
9/91	Large mirror data set with prebunching cavity.	$P \approx 1$ MW, $\eta \approx 30\%$, $f \sim 240$ GHz

Figure VI 4

Milestones $\omega = 2\Omega_{ce}/\gamma$

11/88 Data set on small mirror cavity, diffractive suppression of $\Omega_{ce}|\gamma$. $20\ KW < P < 50\ KW$

$3\% < \eta < 8\%$ $f \sim 240\ GHz$

5/89 Design of feedback system including a filter for $\Omega_{ce}|\gamma$.

11/89 Data set on small mirror double cavity system

$50\ KW < P < 150\ KW$, $f = 240\ GHz$, $8\% < \eta < 25\%$

Figure VI 5

1/90 MIT gun transferred to $2\Omega_{ce}$ laboratory.

5/89 Small mirror, single cavity, 50 KW < P < 150 KW
$3\% < \eta < 8\%$

11/90 Small mirror, double cavity,
200 KW < P < 400 KW, $10\% < \eta < 30\%$
(Lower power because gun not optimal.)

11/91 Large mirror, double cavity, 200 KW < P < 400 KW
CW Relevant Configuration

Figure VI 6

Frequency

50 KG Existing Magnet

$$\frac{\Omega_c}{2\pi\gamma} = 120 \text{ GHz}$$

$$\frac{2\Omega_c}{2\pi\gamma} = 240 \text{ GHz}$$

100 KG Magnet

$$\frac{\Omega_c}{2\pi\gamma} = 240 \text{ GHz}$$

$$\frac{2\Omega_c}{2\pi\gamma} = 480 \text{ GHz}$$

- Slightly higher fields are available and would mean higher frequency. However, compatibility with existing NRL equipment makes the program easier and cheaper at 240 GHz.

- The Q.O. is tunable by magnetic field. 15% tunability at 100 KW and 100 GHz has been demonstrated. 30% tunability should be achievable.

- 5% instantaneous tunability can be achieved by varying the voltage between 60-80 KV.

Figure VI 7

Unit Power

The 4 MW electron gun is an existing piece of hardware and has been ordered. A 1 MW, CW relevant device can be made with existing hardware at 120 GHz. At 240 GHz, a high field magnet or second harmonic operation is required. The heating on the mirrors is compatible with 1 MW CW operation at 280 GHz.

Figure VI 8

Output Mode

The fundamental trade off is that 1 MW CW operation indicates a particular mirror size which, in turn, indicates a particular mode spacing. The crucial goal to be achieved experimentally is to attain mode selective operation. Simulations indicate that the use of a prebunching cavity can achieve single mode operation. Other schemes (i.e., shaped mirrors) will also be investigated. For larger systems some multi moding in a quasi-optical gyrotron could be tolerable because all modes have the same transverse structure.

Figure VI 9

<u>Schedule</u>

The use of a prototype on Alcator C Mod means an aggressive program at the second harmonic and the purchase of a high field magnet. Initial experiments at $2\Omega_c$ would be done with the Seftor gun. However, this also means the immediate purchase of diagnostics at 240 GHz (150K). As NRL has a backup Q.O. magnet, the two experiments could share the modulator and data acquisition system. Early industrial participation would involve the development of the 20 msec modulator, collector, cooling system and window.

Figure VI 10

Cost

CW Varian 60 and 140 GHz gyrotrons at 100 KW level are about \$1/Watt plus power supply and magnet. At the MW level it would be likely to go to 50c/W. (H. Jory, Phone Conversation)

Added Costs for Q.O. Gyrotron

Q.O. Magnet	7c/W	(50 KG)
	20c/W	(100 KG)

Power supply - wide variation depending on the particular system. 80 KV is about as inexpensive a voltage as there is. The cost of the power supply for the quasi-optical gyrotron is as in the MIT proposal.

Best guess for power supply - \$1-2/Watt

Best guess for total cost - \$2-3/Watt

Figure VI 11

Applicability to ETR

The Quasi-Optical Gyrotron has demonstrated the capacity of operation at 120 GHz. Depending on the magnet and harmonic, the operating frequency could be as high as 560 GHz. A follow on program would emphasize issues of efficiency enhancement by optimizing the electron gun design and also by making use of a depressed collector.

Figure VI 12

Capital Costs

Necessary

Diagnostic Equipment at 240 GHz*	150
High Power Sheet Beam Electron Gun@	375
100 KG Q.O. Magnet	250
	775

Prudent but Optional

100 KG KG Backup Magnet$	250
Total of Everything	1025

* Imperative to order immediately.

@ Includes 1 MY of design effort.

$ This admittedly looks expensive, but experience has shown it to be a bargain.

Figure V1 13

Cost of the NRL Program (Personnel and Routine) Per Year (1987K$)

Ph.D Scientists 2.6	250
Engineer and Technicians	225
	475
Routine	250
Total Per Year	725

Total cost of the 4 year NRL program, people, capital and routine is $3925 in 1987K$.

Figure VI 14

PROGRAM COSTS PER YEAR (in 1987K$)

FY88:		
Personnel	475	
Routine	250	
Capital Equipment		
240 GHz Diagnostics	150	
Sheet Beam Gun Design	125	
Total FY88 Cost		1,000
FY89:		
Personnel	475	
Routine	250	
Capital Equipment		
Sheet Beam Electron Gun	250	
100 kG QOG Magnet	250	
Total FY89 Cost		1,225
FY90:		
Personnel	475	
Routine	250	
Capital Equipment		
Backup 100 kG Magnet*	250	
Total FY90 Cost		975
FY91:		
Personnel	475	
Routine	250	
Total FY91 Cost		725
TOTAL PROGRAM COST		3,925

*Optional

Figure VI 15

APPENDIX A

CARM OSCILLATOR RESEARCH AT NRL

1. INTRODUCTION

There is now a considerable effort in the nation to develop high power, high frequency (millimeter wave to infrared) sources based on high voltage electron beams. These devices, the best known of which is the Free Electron Laser (FEL), are inherently high power and produce high frequencies by a doppler-shift effect which scales as the square of the relativistic mass ratio γ. A problem with these devices is that high voltage beams are usually incompatible with compact size, high duty cycle, and affordable cost. For example, the most successful FEL experiment to date, the LLNL 35 GHz device, which produces a GW of peak power from a 3.5 MeV, 850 Amp electron beam, has a pulse length of 20 nanoseconds and a 1 Hz repetition rate. The pulse length is limited by fundamental constraints in the design of the induction linear accelerator and the device is extremely large and expensive. Another impressive FEL experiment, the U.C. Santa Barbara FEL, is based on a 3-6 MV Van de Graff accelerator and operates at wavelengths of 100's of microns. The output power is 40 kW during a 50 microsecond pulse and the rep-rate is 1 Hz. The size of this experiment is also on the scale of a National Laboratory facility.

If this sort of technology is to find use in DoD or DoE systems, the components and power supplies must be made compact, have high duty factor, and be cost effective. For high duty factor operation, it is advantageous to use a thermionic cathode electron gun driven by a high voltage modulator. These modulators are compact, can generate voltages up to 0.5-1 MV, powers up to hundreds of MW's, pulse lengths up to tens of microseconds and rep-rates of several hundred Hz. By making use of depressed collector techniques, modulator performance can be extended to the CW regime. It is therefore of interest to explore the generation of high frequency radiation using electron beams with energies in the 0.5-1 MeV range.

The High Power Electromagnetic Radiation Branch (Code 4740) of the Plasma Physics Division of the Naval Research Laboratory has recently initiated an experimental program in this area with Laboratory/ONR 6.1 funding. The first experiment will be a Cyclotron Auto-Resonance Maser (CARM). Such a device has higher frequency potential than the gyrotron because the wave frequency is doppler-upshifted by ~ γ^2 from the relativistic cyclotron frequency (that is, upshifted by ~γ from the nonrelativistic cyclotron frequency). In fact, for this voltage range higher frequencies are possible than for conventional magnetostatic wiggler FEL's because the wiggler wavelength of such devices is usually limited to about 3 cm. This limits a 1 MeV FEL to

frequencies $\lesssim$ 200 GHz. The efficiency potential of the CARM is similar to the gyrotron - of order 40% - but higher beam quality is required. Compared to gyrotrons, CARM's can have larger cavity structures for a given wavelength and have lower beam pitch angle. These properties simplify beam formation and reduce self-field effects as well as reducing cavity ohmic losses.

Because the interaction occurs with a forward propagating wave, electrons lose axial momentum and axial velocity during the interaction, and this leads high efficiency potential due to an "auto-resonance" effect. That is, the interaction resonance condition

$$\omega = k_z v_z + \Omega_{nr}/\gamma \tag{1}$$

is relatively insensitive to changes in beam energy because the change in the relativistic cyclotron frequency is compensated by a change in the the doppler shift. This effect reduces the detuning of the resonance condition during beam-wave energy exchange. A combination of high doppler upshift of the frequency and high efficiency occurs when $\beta_t = 1/\gamma$ provided that

$$1 - \beta_{ph}^{-2} \lesssim \gamma_o^{-2} \tag{2}$$

where $\beta_t = v_t/c$ and $\beta_{ph} = v_{ph}/c$. The autoresonance effect leads to high efficiencies without the need for efficiency enhancement

schemes based on tapering the interaction parameters. This is in contrast to the FEL which depends on tapering to achieve high efficiency.

A 0.5 MV CARM has the potential for efficient, multi-MW operation at wavelengths of 1.1 mm (280 GHz) with a 63 kG superconducting magnet or 560 GHz with a 125 kG magnet. With a 1 MV beam or operation at harmonics there is a potential for THz frequencies. This potential makes the CARM an attractive candidate for development as a source for CIT.

The NRL development effort has chosen to conduct its first experiments on CARM oscillator configurations for several reasons. The CARM circuit generally involves a highly overmoded waveguide structure with the attendant probability of mode competition. Compared to the amplifier, the oscillator configuration appears to offer more alternatives for mode control. Waveguide cavities with rippled-wall Bragg reflectors can be highly selective with respect to frequency and axial mode index. On the other hand, quasi-optical cavities have excellent transverse mode selectivity. Because the radiation traverses an oscillator cavity many times instead of once as in an amplifier, the interaction length can be relatively short and this helps prevent the build-up of spurious oscillations which are a major issue for amplifiers, particularly at high frequencies. The short interaction length also helps reduce the sensitivity to

beam velocity spread. Additionally, a free running oscillator does not require a source of input power, an expensive and scarce commodity at submillimeter wavelengths. The CARM also requires an overmoded but highly mode selective and nonbeam-intercepting input coupler, a difficult engineering problem.

The efficiency potential of CARM oscillators and amplifiers appears to be similar, of order 20-40%. The circulating power in a high Q oscillator is generally much greater than the output power. This leads to somewhat greater Ohmic losses for a given output power for the oscillator compared to the amplifier, however. as discussed below, oscillators can be designed for megawatt CW powers.

The remainder of this appendix gives a brief description of the ongoing and planned NRL CARM programs.

2. TECHNICAL DESCRIPTION OF THE NRL PROGRAM

NRL currently has an ongoing short pulse (~50 nsec), 100 GHz CARM oscillator experiment supported by Laboratory 6.1 funding. This experiment is being conducted by Dr. R. B. McCowan. In FY88 this research effort will transition to a new 6.1 funded project to develop a 200-300 GHz CARM oscillator based on a 0.5 MV electron beam produced by a thermionic cathode electron gun. The key experimental physicist for this project will be Dr. McCowan. The device would have a pulse length of 1 microsecond and be rep-

rated. The goal of the "long pulse" experiment would be to achieve an output powers of about 10 MW and efficiencies in the 20-40% range. A 50 kG superconducting magnet would be used. The oscillator design involves a MIG type electron gun and the use of a waveguide cavity with Bragg reflectors. Quasi-optical cavity designs and CARM-related CRM configurations such as the IREC would also be investigated. Possible follow-on experiments to a successful oscillator experiment could be a CARM pumped electromagnetic wiggler FEL experiment, an 85-100 GHz amplifier, or a CARM operated at a harmonic of the cyclotron frequency.

Ongoing Short Pulse CARM Experiment

NRL has already made significant progress in a 6.1 supported research effort to develop CARM amplifiers and oscillators. A comprehensive theory of the CARM interaction in a waveguide has been formulated.[14] In FY86 a short pulse 100 GHz CARM oscillator experiment based on a 600 kV, 55 nsec Febetron pulser was initiated and is being conducted by Dr. R. McCowan. A schematic of the device which is in the fabrication and set up stage is shown in Figure A 1. The design parameters are summarized in Table A.1. The dispersion relationship for the uncoupled cavity and beam modes is shown in Figure A 2. This figure shows how the interaction frequency is doppler upshifted from the cyclotron frequency. The wave frequency is also significantly above the

mode cutoff frequency which leads to a correspondingly larger cavity diameter. An experimental design has been developed which addresses the key CARM issues of beam quality and mode selectivity. It features a Bragg reflector cavity and an innovative cold cathode diode with nonemitting focussing electrodes. The cathode is anodized aluminum with a velvet emitting surface. The diode is expected to produce a high quality beam with only a few percent spread in axial momentum. This diode, shown in Figure A 3, represents the first test of a theory of relativistic laminar flow diodes recently developed at NRL by Finn, Fliflet and Manheimer.[29] The ability to produce a high quality beam is considered critical to the success of this experiment, a major objective of which is to demonstrate high efficiency for the CARM interaction. The beam quality requirement can be estimated by a simple coherence argument. The constraint on axial velocity spread is

$$\Delta v_z/v_z < \frac{1}{2}\lambda/L \qquad (3)$$

for no spread in beam energy. Eq.(3) can readily be expressed as a constraint on pitch angle spread. The constraint on energy spread for a beam with no pitch angle spread is

$$\frac{\Delta\gamma}{\gamma} < \frac{(1-\gamma_o^{-2})}{(1+\alpha^2)(\frac{\Omega}{\omega}-\gamma_o^{-2})}\frac{\lambda}{2L} \qquad (4)$$

These relationships lead to the curves for axial momentum, pitch angle, and energy spread shown in Figure A 4 for a 600 kV CARM ($\beta_t = 1/\gamma_o$). These curves show that there is greater sensitivity to pitch angle spread than to energy spread, a feature related to the auto-resonant character of the interaction. Note that the denominator of Eq.(4) can be small when $\gamma_o >> 1$ since in this case for the CARM $\omega/\Omega \approx \gamma^2$. The required tolerances are considered achievable except for group velocities extremely close to the speed of light. A group velocity of 0.86c was chosen for this experiment.

An important feature of the Bragg reflector cavity is that it is has a high Q factor for only a limited range of axial wavenumbers. Our design studies for the 100 GHz CARM experiment indicate that this type of cavity can be highly selective with respect to both transverse and longitudinal mode indices. Other advantages of this type of resonator include compactness which facilitates beam transport and magnet design, and the possibility of profiling the cavity fields for efficiency enhancement similarly to what is done for gyrotrons. A Bragg cavity and associated radiation profile are shown in Figure A 5. The depth of the Bragg ripples is considerably exaggerated. The TE_{61} whispering gallery mode was chosen as the operating mode. This type of mode couples well to both the electron beam and to the Bragg reflectors. The frequencies and Q factors of the high Q

modes for this cavity are shown in Figure A 6. In this cavity, there is only a single axial mode per transverse mode. The CARM mode Q factor is chosen high enough to prevent competition from low frequency gyrotron modes.

The cavity and beam parameters used in this design are based on the theoretical study of the CARM interaction given in Ref. 14. The interaction is modeled by the equations shown in Figure A 7 and the scaling of the normalized (bunching) efficiency for a constant amplitude wave and fundamental harmonic is shown in Figure A 8. The efficiency scaling for the first four harmonics is shown in Figure A 9. In Figures A 8 and A 9 the CARM regime corresponds to the electron recoil parameter $b \sim 0.5$. The computed cold beam electronic efficiency is 20% for this configuration with a potential for 40% using an optimized radiation amplitude profile. A mode map of competing modes encountered during the start-up process (rise of voltage pulse) is shown in Figure A 10. According to Figure A 10, the operating mode (TE_{61}) is relatively free from mode competition at 600 kV. The magnetic field used in Figure A 10 corresponds to high efficiency operation.

<u>NRL Long Pulse CARM Research</u>

The present 600 kV, 100 GHz CARM oscillator project is expected to provide important data on the potential of the CARM as an efficient high power source. However, a thermionic cathode

experiment is essential for complete investigation of CARM issues. The data rate and accuracy of diagnostics - particularly of coherence - are dramatically improved in a rep rated, microsecond time scale experiment. A modulator can provide the relatively flat voltage pulse which is needed for efficient, single mode operation. A microsecond beam pulse is also necessary for investigation of quasi-optical cavities (IREC's) which have a longer fill time. Finally, such an experiment would serve as a directly relevant prototype of the proposed high energy, high duty factor sources.

A preliminary design has been obtained for a 500 kV, 250 GHz device shown schematically in Figure A 11. The design parameters are given in Table A.II. A 55 kG magnetic field is required. A TE_{14} mode has been chosen based on output power, e-beam size, and wall heating considerations. The cavity radius is 9.3 mm and the electron beam radius for a beam placed on the third E-field peak - this avoids coupling to whispering gallery modes - is 5.6 mm. An annular electron beam is generated by a temperature-limited MIG type 500 kV electron gun. For a cathode with a maximum emission current density of 10 A/cm^2 and a current of 100 Amps, the average cathode emitter radius could be about 3 cm leading to a magnetic field compression radio of ~30, which is well within MIG gun state-of-the-art. The gun perveance is 0.28 micropervs. For comparison, the gun for the SLAC klystron has a

perveance of 2 micropervs, thus space-charge defocussing effects should be controllable. Very low pitch angle spread (a critical CARM requirement) have been obtained with this type of gun and the design goal is an axial momentum spread of a few percent.

A TE_{14} mode and a group velocity of 0.97c were chosen for the preliminary design. An output power of 10 MW is obtained for 92% output reflectivity and the wall loading is about 3 kW/cm^2. The peak electric fields at the wall are less than 50 KV/cm. Operation at 10% duty factor would result in an average power of 1 MW and an average wall loading of 0.3 kW/cm^2. The computed cold beam efficiency is 38% and the required beam current is 53 Amps. This experiment should provide highly a relevant technology base for a burst mode 280 GHz source for CIT or Alcator C-Mod.

An important experimental objective will be oscillator operation in volume TE modes such as TE_{0n} or TE_{1n} type modes. Such modes have much lower wall losses due to ohmic heating and peak rf fields at the wall than whispering gallery (TE_{m1}) modes and are therefore of interest for high duty factor applications. However, special cavity designs are required to select these modes. Possible approaches include the use of axial slots to select TE_{1n} modes or suppression of axial currents (wire-walled waveguide) for TE_{on} modes. In addition, high reflectivity Bragg type reflectors have not as yet been developed for volume modes

with weak induced wall currents. Quasi-optical cavity configurations will also be investigated. The attractiveness of such cavities increases with increase in the radiation frequency since for high power it becomes necessary to increase cavity size relative to the wavelength. Open mirror quasi-optical cavities also allow the wave phase velocity to be controlled independently of the transverse mode or transverse dimensions of the cavity. As discussed by Sprangle et al.[1], this control is obtained by varying the angle between the radiation and beam propagation directions. Quasi-optical cavities have excellent transverse mode selectivitiy and should not support low frequency (gyrotron) modes; however, longitudinal mode selection may a problem as in quasi-optical gyrotrons.

250 GHz CARM Oscillator Program Plans

Design of the electron gun, the longest lead time item, would begin in FY87. The short pulse CARM device is being used as a CARM research test-bed during FY87. Procurement of the 50 MW, 500 kV thermionic electron gun with Plasma Physics Division Asset Capitalization Program (ACP) funds will occur in FY88. The procurement of a 500 kV modulator with ACP funds is planned for FY89. An experimental facility for long pulse CARM research would be set up in FY89. Experimental studies of the CARM oscillator are expected to commence in FY90 and continue through FY91.

FUNDING PROFILE

FY88: 250 K 6.1 support, 300 K ACP funds for electron gun.
Level of effort: 2 PY

FY89: 400 K 6.1 support, 200 K ACP funds for modulator.
Level of effort: 2.5 PY

FY90: 500 K 6.1 support.
Level of effort: 3 PY

FY91: 500 K 6.1 support.
Level of effort: 3 PY

Follow-on Experiments

The design of high power, wide bandwidth CARM amplifiers could be considered as a follow-on to the CARM oscillator experiments. The linear and non-linear theory of CARM amplifiers is treated in Ref. 14. Design examples for MeV beams given in this work have efficiencies over 20% and are readily scalable to 500 keV beams and multi-MW output powers. Since amplifiers are considered to have more stringent requirements for beam quality and spurious mode suppression, and require a relatively powerful input source, CARM amplifier experiments would be carried out at

lower frequencies (85-100 GHz) and in the fundamental TE_{11} circular waveguide mode or other low order mode. The High Power Electromagnetic Radiation Branch has a 1 kW 85 GHz EIO available as an input source. Other interesting follow-on experiments include a two stage FEL/CARM infrared experiment and CARM harmonic operation.

TABLE A.I

TABLE I: PARAMETERS OF 100 GHz SHORT PULSE CARM EXPERIMENT

Electron Beam	
Diode Type	limited emission, cold cathode
Beam Cross Section	annular
Beam Diameter	1.2 cm
Beam Voltage	600 kV
Beam Current	150-200 Amp
Pulse Width	20 nsec
Velocity Pitch Ratio	0.6
Pitch Angle Spread Limit	8 %
Energy Spread Limit	11 %
Resonator	
Cavity Type	circular waveguide
Reflector Type	rippled-wall Bragg reflector
Operating Mode	TE_{61} "whispering gallery"
Wave Group Velocity	0.87c
Cavity Length	10 cm
Cavity diameter	1.8 cm
Cavity Q	1500
Magnet	
Magnet Type	pulsed solenoid
Cavity Magnetic Field	23 kG
Predicted Efficiency	20 %
Predicted Output Power	20 MW

TABLE A.II

TABLE II: PRELIMINARY DESIGN PARAMETERS OF
250 GHz LONG PULSE CARM EXPERIMENT

Electron Beam	
Gun Type	temperature-limited MIG
Beam Cross Section	annular
Beam Diameter	1.1 cm
Beam Voltage	500 kV
Beam Current	100 Amp max.
Pulse Width	1 μsec
Velocity Pitch Ratio	0.71
Pitch Angle Spread Limit	2 %
Energy Spread Limit	7 %
Resonator	
Cavity Type	circular waveguide
Reflector Type	Bragg reflector
Output Reflectivity	92 %
Operating Mode	TE_{14} (volume mode)
Wave group Velocity	0.97c
Cavity Length	~ 10 cm
Cavity diameter	1.8 cm
Ohmic Heating	3 kW/cm^2
Magnet	
Magnet Type	superconducting
Cavity Magnetic Field	~ 55 kG
Predicted Efficiency	20-40 %
Predicted Output Power	10 MW

SCHEMATIC OF 100 GHz SHORT PULSE CARM OSCILLATOR

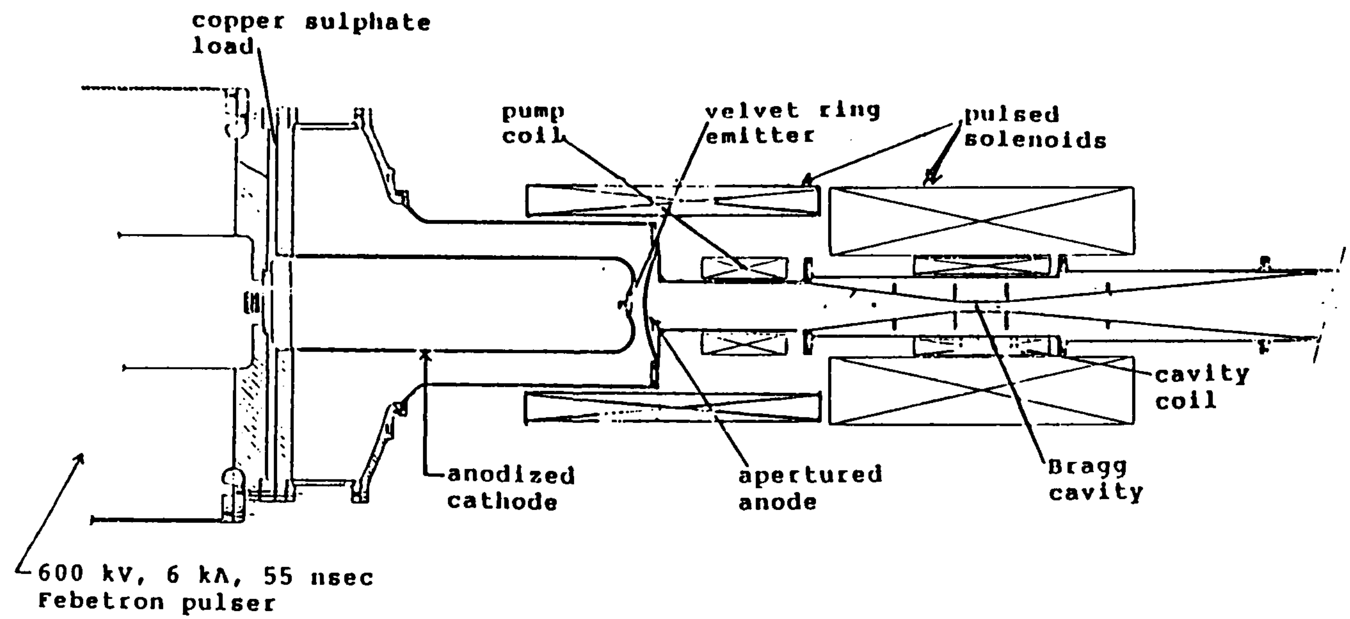


FIGURE A 1

CARM Dispersion Relation

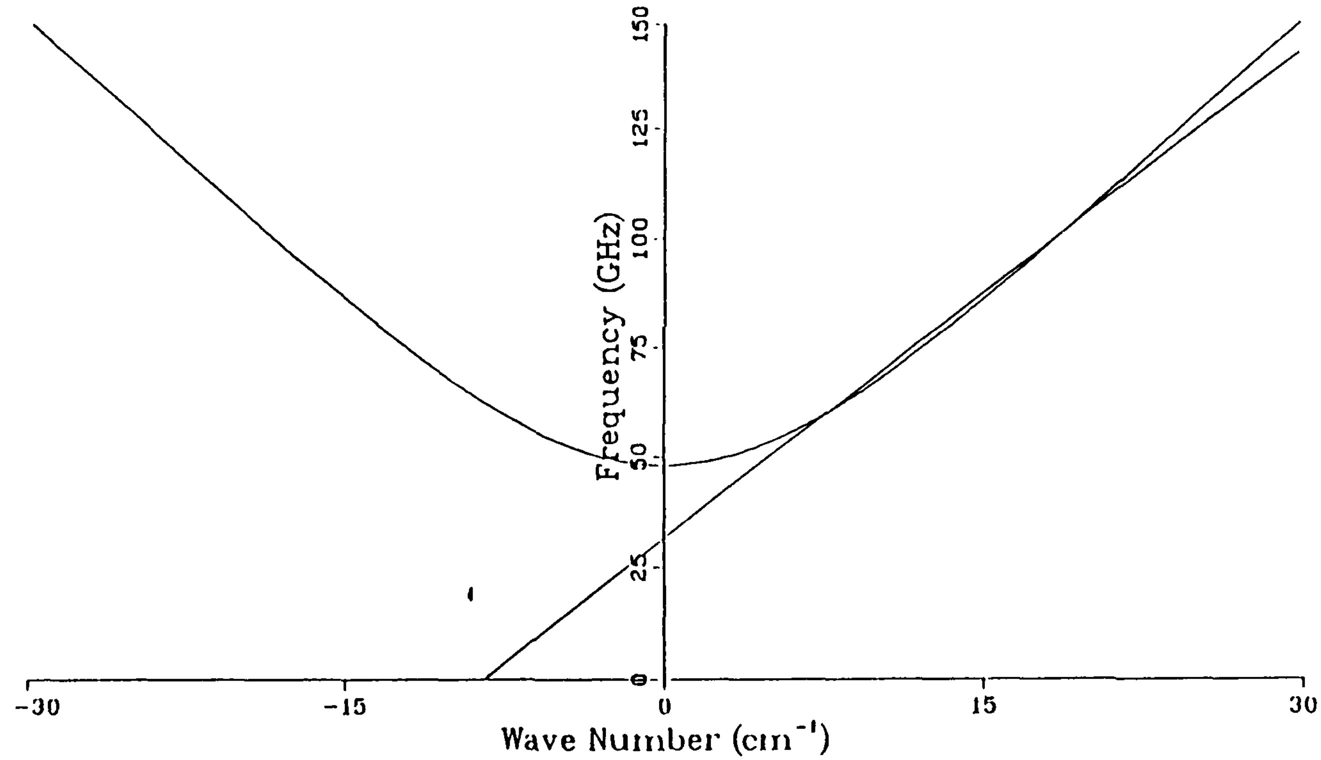
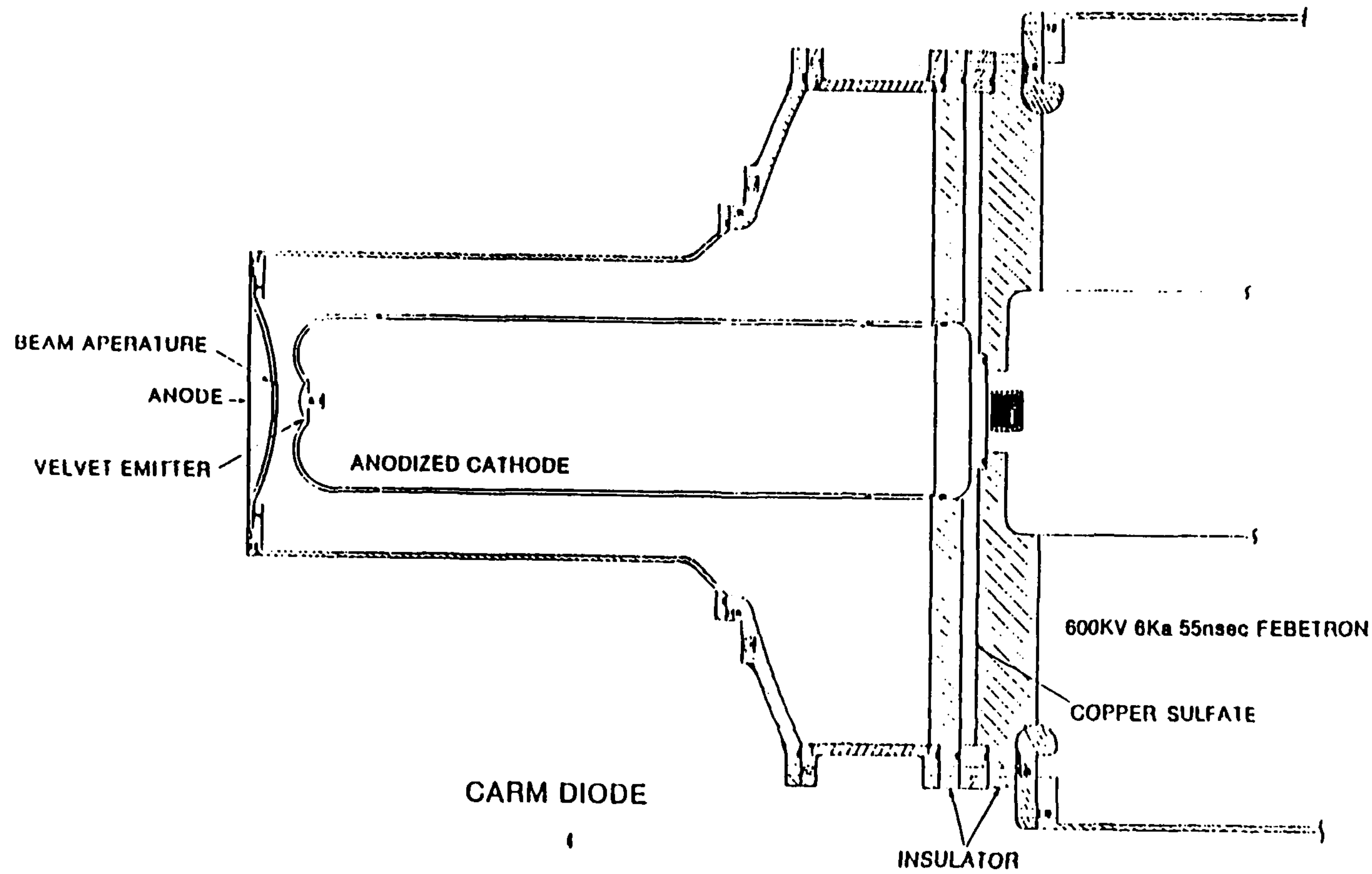


FIGURE A 2



CARM DIODE

FIGURE A 3

CARM OSCILLATOR

Beam Quality Requirements

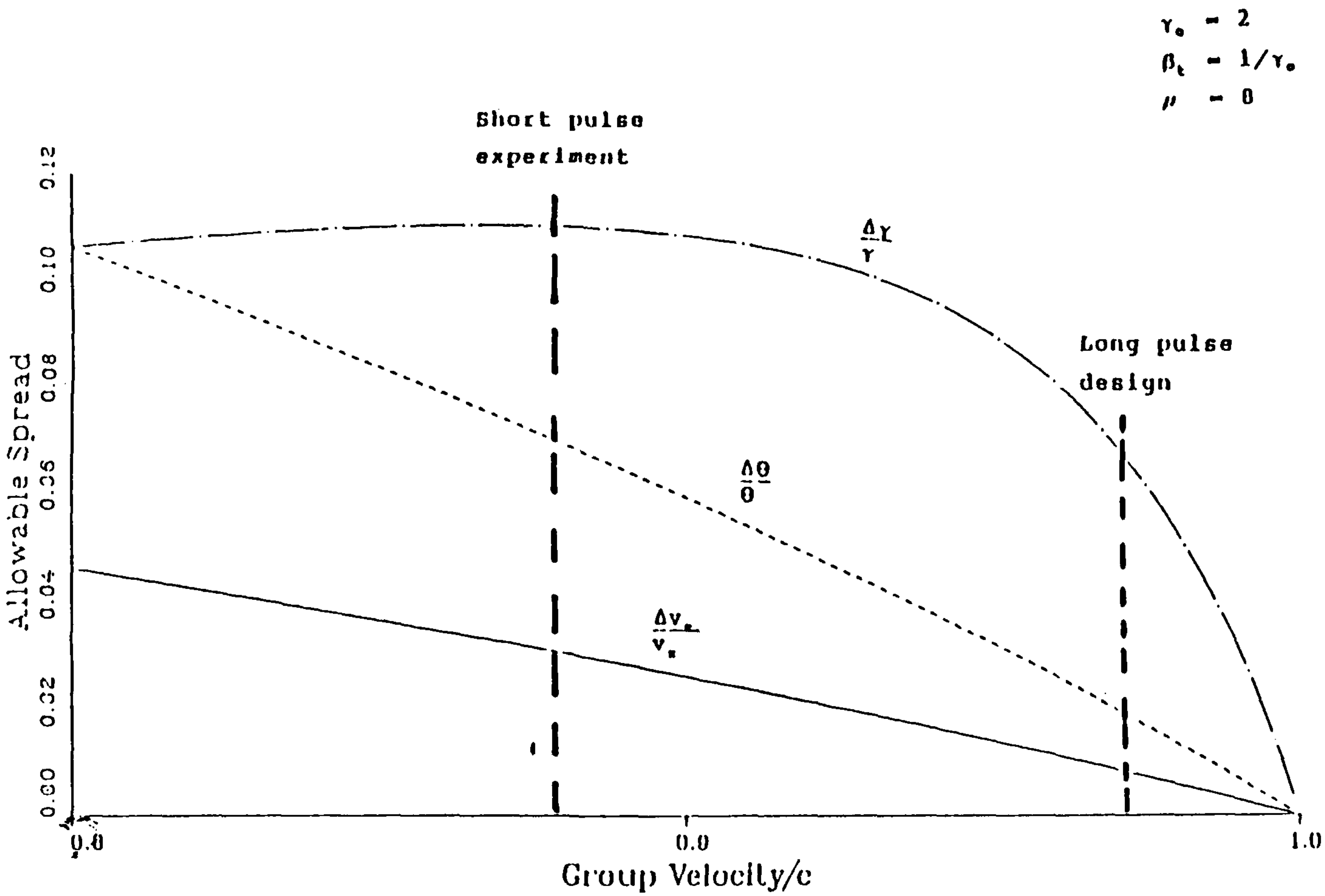


FIGURE A 4

Bragg Resonator Profile

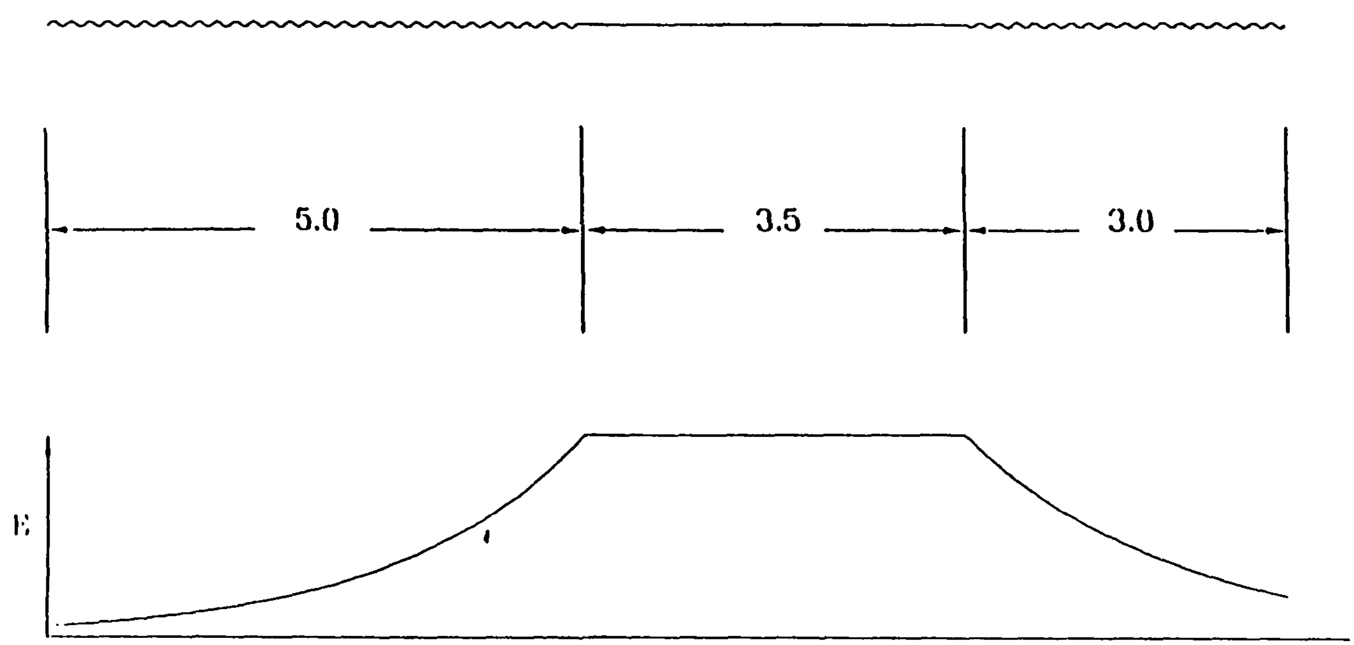
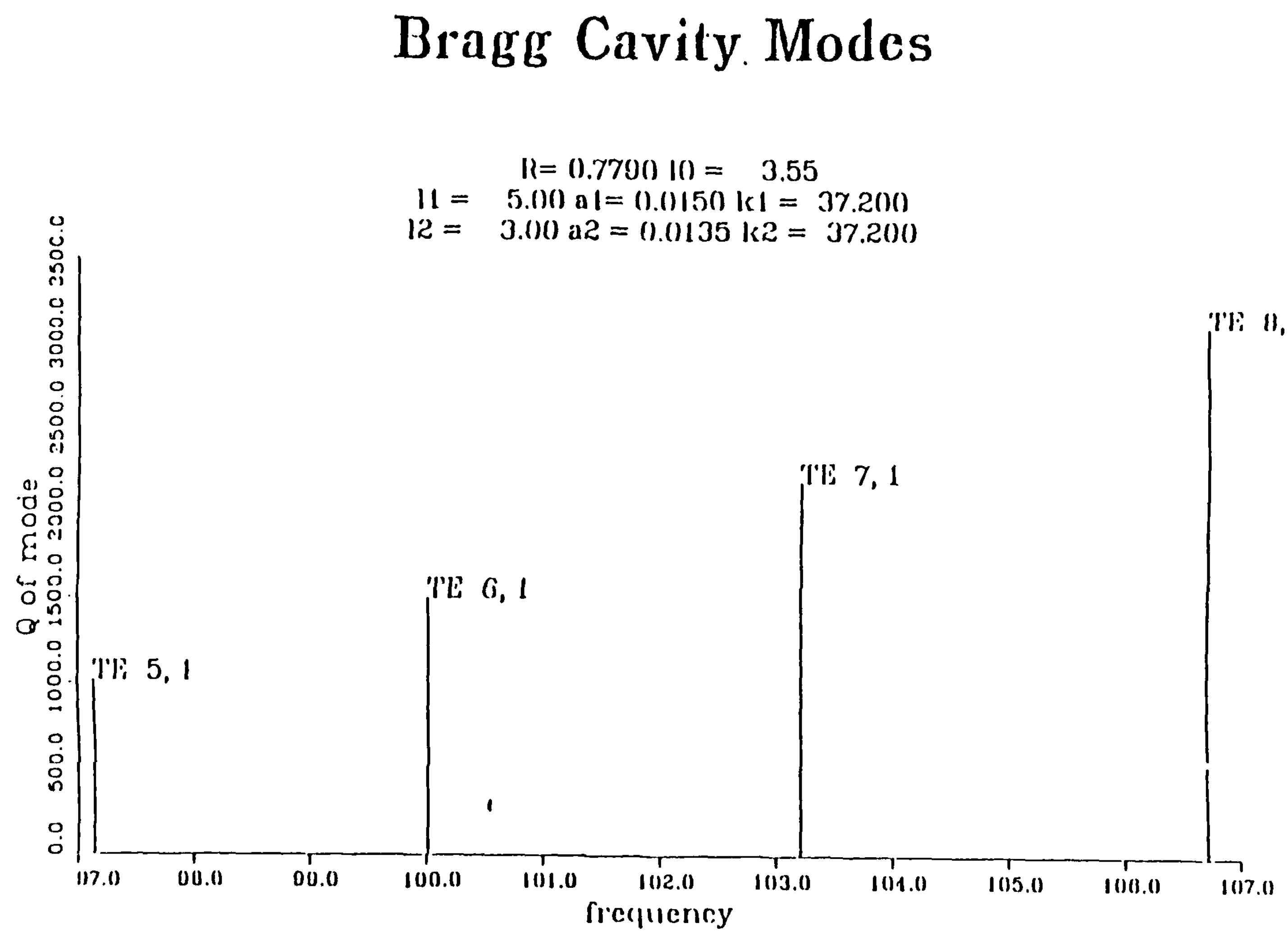


FIGURE A 5



Bragg Cavity Modes
R= 0.7790 l0 = 3.55
l1 = 5.00 a1= 0.0150 k1 = 37.200
l2 = 3.00 a2 = 0.0135 k2 = 37.200
Q of mode
0.0 500.0 1000.0 1500.0 2000.0 2500.0 3000.0 3500.0
TE 5, 1
TE 6, 1
TE 7, 1
TE 8, 1
100.0 101.0 102.0 103.0 104.0 105.0 107.0
frequency

Figure A 6

GENERALIZED CYCLOTRON RESONANCE MASER THEORY

Application of single particle theory to CRM interaction leads to Generalized Pendulum Equations:

$$\frac{du}{d\zeta} = \frac{(1-u)^{s/2}}{1-bu} \mathrm{Re}\{F_s e^{-i\theta}\}$$

$$\frac{d\theta}{d\zeta} = [\Delta - u + \frac{s}{2}(1-u)^{s/2-1} \mathrm{Re}\{iF_s e^{-i\theta}\}] / (1-bu)$$

where u is the normalized energy:

$$u = \frac{2}{\beta_{to}^2}(1 - \frac{\beta_{zo}}{\beta_{ph}})(1 - \frac{\gamma}{\gamma_o}), \qquad \beta_{to} = \frac{v_{to}}{c},$$

θ is a slowly varying phase, and ζ is the normalized axial coordinate

$$\zeta = \frac{\beta_{to}^2}{2\beta_{zo}} \frac{(1-\beta_{ph}^{-2})}{(1-\frac{\beta_{zo}}{\beta_{ph}})} \frac{\omega z}{c} \qquad [\mu = \zeta(z=L)]$$

The normalized efficiency $\hat{\eta} = \int_0^{2\pi} u(\mu,\theta_o)d\theta_o$ depends only on the harmonic s, the detuning parameter

$$\Delta = \frac{2}{\beta_{to}^2} \frac{(1-\frac{\beta_{zo}}{\beta_{ph}})}{(1-\beta_{ph}^{-2})} (1 - \frac{\beta_{zo}}{\beta_{ph}} - \frac{s\Omega}{\omega}),$$

the length μ, the wave amplitude F_s, and the electron recoil parameter

$$b = \frac{\beta_{to}^2}{2\beta_{zo}\beta_{ph}\ (1-\frac{\beta_{zo}}{\beta_{ph}})}$$

which characterizes the change in axial momentum during interaction.

Figure A 7

OPTIMUM NORMALIZED EFFICIENCY FOR CONSTANT AMPLITUDE WAVE

AND FUNDAMENTAL HARMONIC

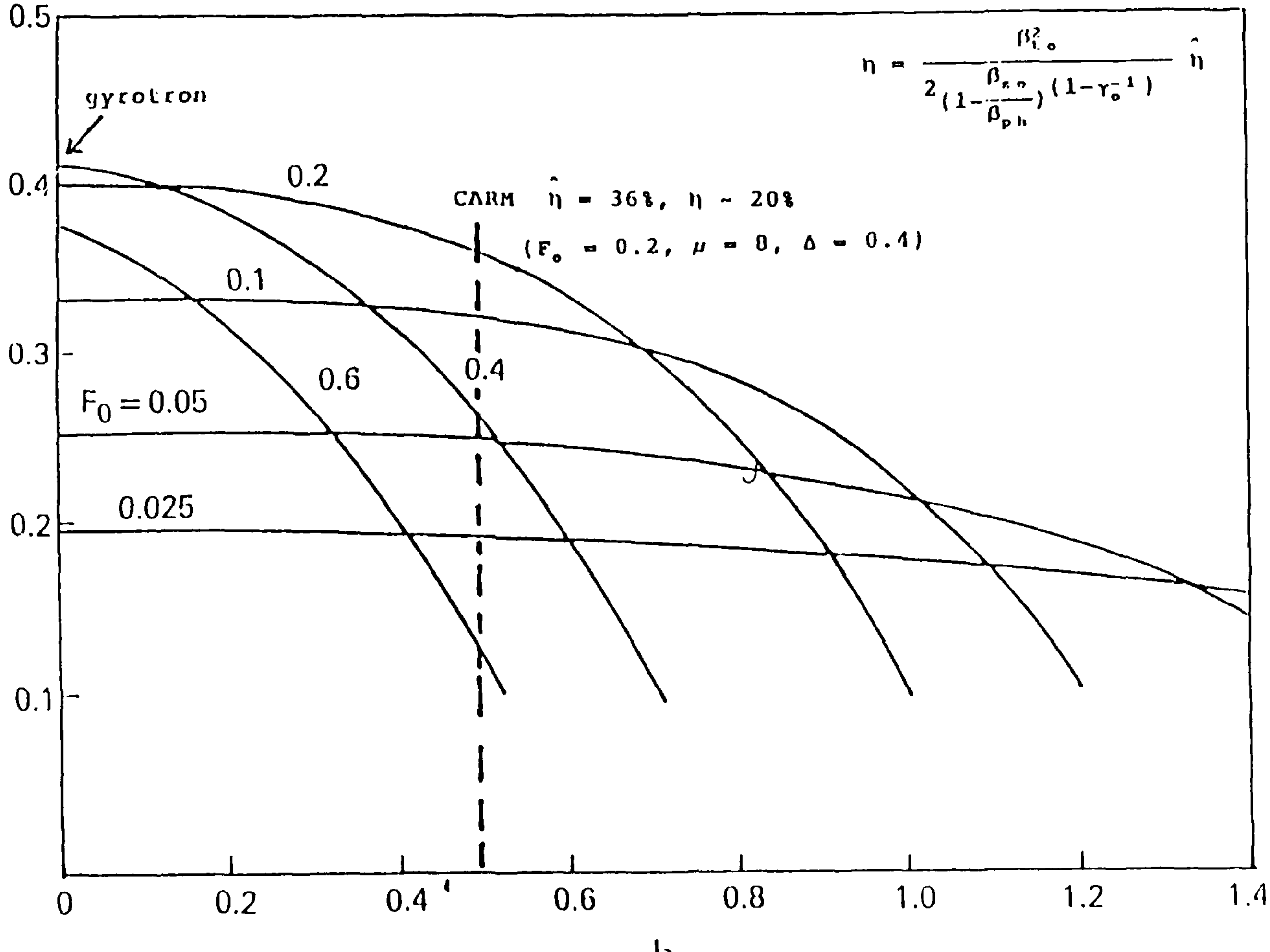


Figure A8

OPTIMUM NORMALIZED EFFICIENCY FOR HARMONICS

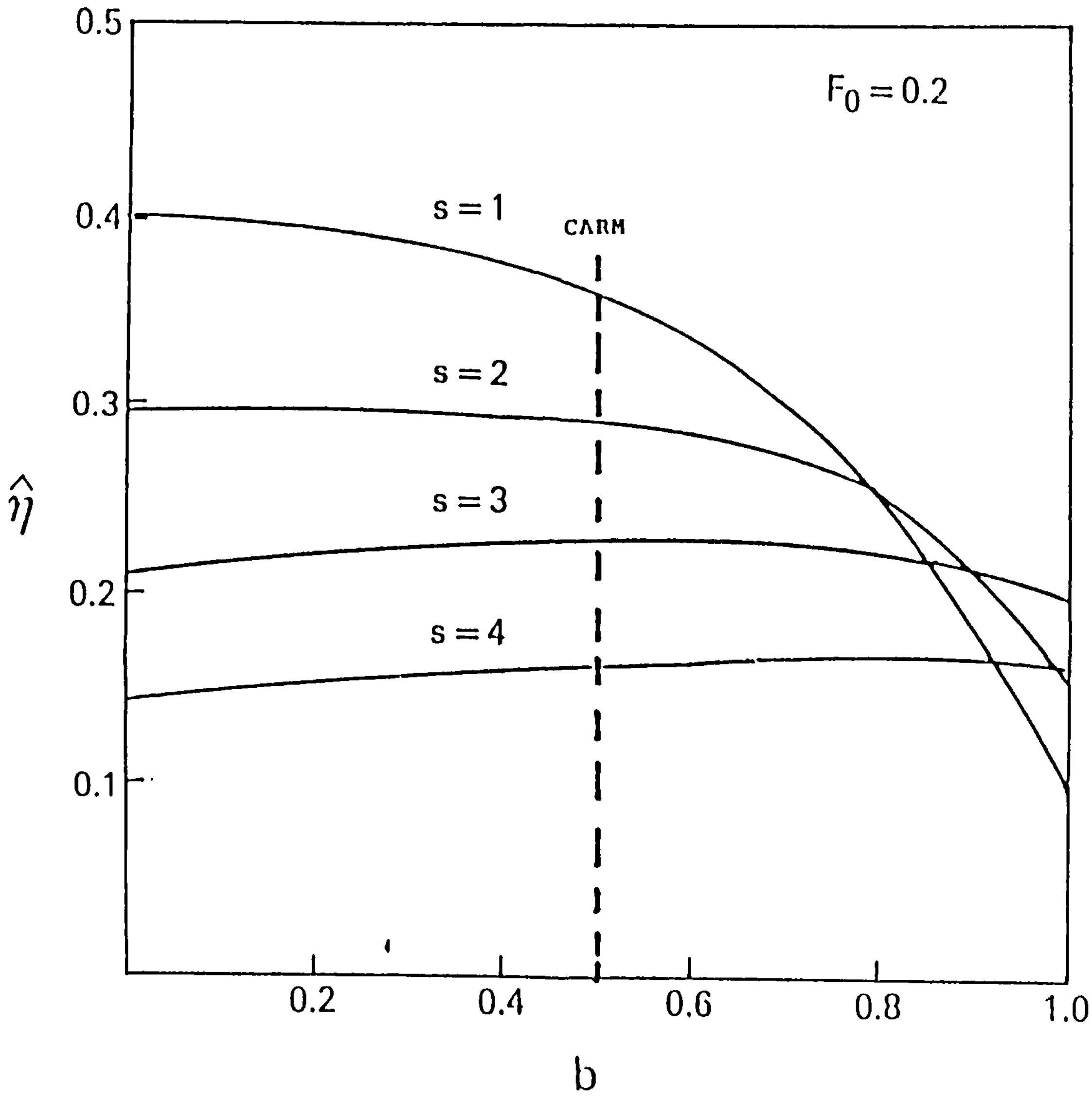


Figure A9

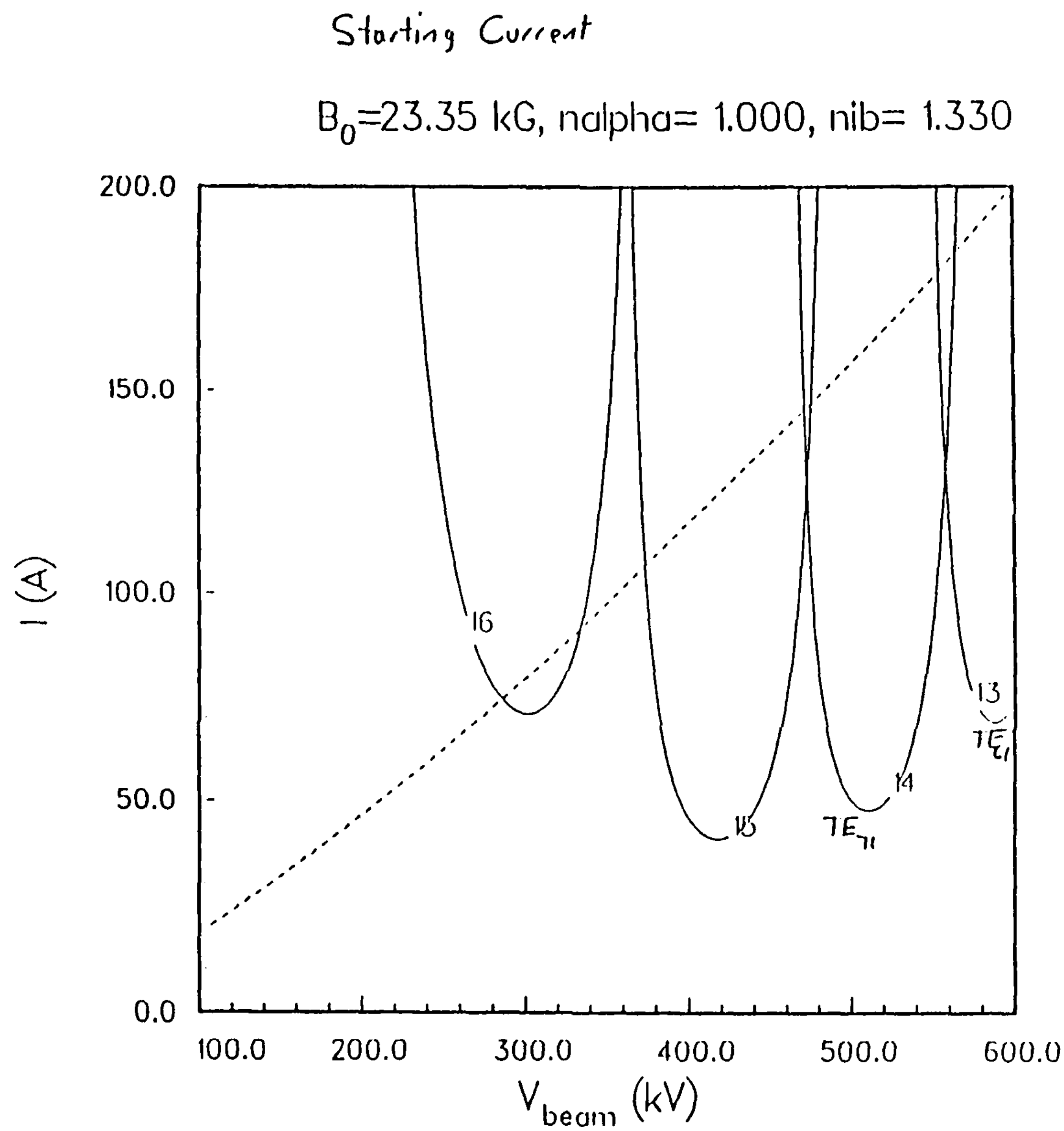

Starting Current
B_0=23.35 kG, nalpha= 1.000, nib= 1.330
200.0
150.0
100.0
50.0
0.0
I (A)
16
15
14
13
TE_{71}
TE_{61}
100.0
200.0
300.0
400.0
500.0
600.0
V_{beam} (kV)

Figure A10

SCHEMATIC OF PROPOSED 250 GHz LONG PULSE CARM OSCILLATOR

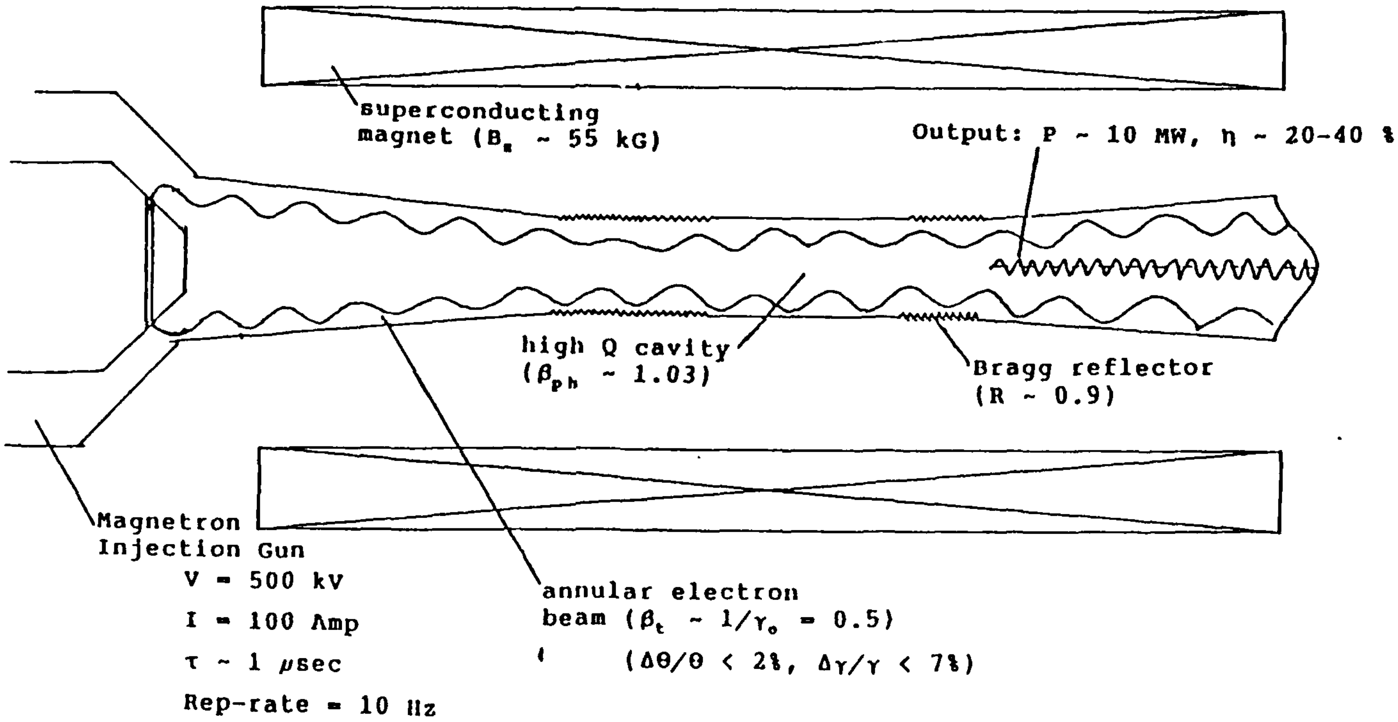


Figure A11

Appendix B

BIOGRAPHICAL OUTLINES AND PUBLICATION LISTS

1. Biographical Outlines

Dr. Wallace Manheimer is head of the High Power Electromagnetic Radiation Branch (Code 4740) at the Naval Research Laboratory. He has had twenty years experience in plasma physics and high power microwave radiation production. He has been involved for ten years in both the development of rf sources for electron cyclotron resonance heating, and also in the development of the theory of ECRH. He holds a patent for both the quasi-optical gyroklystron oscillator and the quasi-optical harmonic gyrotron.

Dr. Arne Fliflet is head of the Advanced Concepts and Free Electron Section of the High Power Electromagnetic Radiation Branch at the Naval Research Laboratory. He has had 8 years experience in research on the development of Cyclotron Resonance Masers (gyrotrons). He has made contributions to the theory of the operation of low-Q gyrotron oscillators, gyrotron resonator and electron gun design, and cyclotron auto-resonance masers (CARMs). He has been involved in experimental projects to investigate gyroton oscillators for ECRH, high voltage pulsed gyrotrons, phase-locked gyrotrons, and CARMs.

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122. "Electron Orbits in Combined Rotating Quadrupole and Dipole Magnetic Fields," B. Levush, T. M. Antonsen and W. M. Manheimer, J. Applied Phys. 59, 2634 (1986).

123. "One Dimensional Models for Relativistic Electron Beam Diode Design," J. M. Finn, A. W. Fliflet and W. M. Manheimer, Intl. J. Electronics (Gyrotrons IV) 61, 985 (1986).

124. "Self Field Effects in Gyrotrons," T. M. Antonsen, W. M. Manheimer and B. Levush, Intl. J. Electronics (Gyrotrons IV) 61, 823 (1986).

125. Subnanosecond Millimeter Wave Pulse Production with a Phase Modulated Quasi-Optical Gyrotron," W. M. Manheimer and M. R. Read, Intl. J. Electronics (Gyrotrons IV) 61, 1041 (1986).

126. "The Eigenfunctions of Open Resonators," S. McDonald, J. Finn, M. Read and W. Manheimer, Intl. J. Electronics (Gyrotrons IV) 61, 795 (1986).

127. "Spontaneous Radiation of an Electron Beam in a Free Electron Laser with a Quadrupole Wiggler," B. Levush, T. M. Antonsen and W. M. Manheimer, J. Appl. Phys., to be published.

128. "High Peak Power K_a-Band Gyrotron Oscillator Experiment," S. H. Gold, A. W. Fliflet, W. M. Manheimer, R. B. McCowan, W. M. Black, R. C. Lee, V L. Granatstein, A. Kinkead, D. L. Hardesty and M. L. Sucy, Phys. Fluids, to be published.

129. "Theory of the Multi-Cavity Phase Locked Gyrotron Oscillator," W. M. Manheimer, Intl. J. Electronics, to be published.

130. "Space Charge Limited and Temperature Limited Electron Flow in the Vicinity of Edges and Conical Points," J. M. Finn, T. M. Antonsen and W. M. Manheimer, Int. J. Electronics, to be published.

Books

1. Weak Turbulence Theory of Velocity Space Diffusion in a Magnetic Field. Contributed to "Plasma Waves in Space and in the Laboratory", Edited by J. O. Thomas and B. J. Landmark, Edenburgh University Press, 1970, p. 523.

2. Introduction to Tokamak Trapped Particle Instability, Wallace M. Manheimer, ERDA Critical Review Series (1977).

3. Electron Cyclotron Resonant Heating of Tokamaks, W. Manheimer, Millimeter and Infrared Waves. K. Button, Editor, Academic Press 1979, Vol. II.

4. An MHD Instability Primer, W. M. Manheimer, U.S. Government Printing Office, 1984.

5. The General Nonlinear Theory of Free Electron Laser and Efficiency Enhancement, in Physics of Quantum Electronics, P. Sprangle, C. M. Tang and W. Manheimer, Vol. 7, Teluride, CO, 1979.

6. Multimode Analysis of Quasi-Optical Gyrotrons and Gyroklystrons, A. Bondeson, W. M. Manheimer and E. Ott, Millimeter and Infrared Waves, K. Button, Ed. Academic Press, 1983, Vol. 9, p. 309.

7. Theoretical Investigation of the Application of Quasi-Optical Open Resonators to the Electron Cyclotron Maser, J. L. Vomvoridis, P. Sprangle and W. Manheimer. Ibid Vol. 7, p. 487 (1983).

8. Marginal Stability Analysis - A Simpler Approach to Anomalous Transport in Plasmas, W. Manheimer and J. Boris, in A Perspective of Physics, Vol 2, p. 207, Sir Rudolph Peierls, ed. Gordon and Breach, 1978.

9. The Theory of the Axially Injected TEM Orbitron Maser, J. Burke, W. Manheimer and E. Ott, Proceedings of the IEEE Short Course on High Power Microwave, to be published.

Patents

1.	U.S. Patents 4,115,191	Tokamak Plasma Heating with Intense, Pulsed Ion Beams, E. Ott and W. Manheimer.
2.	U.S. Patent 4,143,229	Charged Particle Beam Acceleration in a Converging Waveguide, P. Sprangle, A. Drobot and W. Manheimer.
3.	U.S. Patent 4,421,713	Intense Pulsed Ion Beam Driven Tokamak, W. Manheimer and N. Winsor.
4.	U.S. Patent 4,548,782	Tokamak Plasma Heating with Intense Pulsed Ion Beams, W. Manheimer and N. Winsor.
5.	U.S. Patent 4,491,756	Quasi-Optical Gyrokystron, W. Manheimer, A. Bonderson and E. Ott.
6.	U.S. Patent 4,559,475	Quasi-Optical Harmonic Gyrotron and Gyroklyotron, W. Manheimer and Baruch Levush.
7.	U.S. Patent 4,608,537	A Low Perturbation Electron Injector for Cyclic Accelerators, F. Mako, W. Manheimer, C. Kapetanakos and F. Sandel.
8.	Navy Case 68,747	Plasma Assisted Modified Betatron, Wallace Manheimer.
9.	Navy Case 69,383	Plasma Microwave Pulse Compression, B. H. Ripin and W. M. Manheimer.
10.	Navy Case 69,949	A Pod Mounted High Power Microwave Weapon and ew Device, A. Kinkead, S. H. Gold, A. W. Fliflet and W. M. Manheimer.
11.	U.S. Patent 4,548,782	Tokamak Plasma Heating with Intense Pulsed Ion Beams, W. M. Manheimer and N. K. Winsor.

12. Axial Injection TEM Orbitron, J. Burke and W. Manheimer.

13. Short Microwave Pulse Generation with a Phase Modulated Quasi-Optical Gyrotron, M. Read and W. Manheimer.

NRL Memorandum Reports and other unpublished reports

Many of the journal articles listed were also published in preliminary form as NRL Memorandum Reports and these are not listed separately. However there are several other memos and/or submissions in classified meeting proceedings which did not seem appropriate as publications in archival journals because they served more as reports, commentaries, tutorials, or were classified.

1) Report to the Atomic Energy Commission on the NRL Studies Concerning the Two Component Torus Concept. J. P. Boris, K. R. Chu, J. H. Gardner, W. M. Manheimer, K. Papadopoulos, C. E. Wagner and N. K. Winsor, NRL Memorandum Report 2878.

2) A General Derivation of the Conservation Equation for Wave Action. W. Manheimer, NRL Memorandum Report 3008, April 1975.

3) Anomalous Transport Coefficients for HANE Applications due to Plasma Micro-Instabilities. M. Lampe, W. M. Manheimer and K. Papadopoulos, NRL Memorandum Report 3076, June 1975.

4) The Status of the Nonlinear Theory of Drift and Trapped Particle Instabilities. W. M. Manheimer, NRL Memorandum Report 3369, September 1976.

5) Development of High Power, Millimeter-Wave Cyclotron Masers at NRL and its Relevance to CTR. W. M. Manheimer and V. L. Granatstein, NRL Memorandum Report 3493, July 1977.

6) Shear Stabilization of Drift Waves in Noncircular Cross Section Axisymmetric Configurations. E. Ott, W. M. Manheimer and K. R. Chu.

7) What Do Fluctuation Measurements Say About $D = \gamma/k^2$ and Shear Stabilization of Drift Waves? I. Cook and W. Manheimer, NRL Memorandum Report 3913, January 1979.

8) Some NRL Thoughts on Microwave Directed Energy (U). W. M. Manheimer, NRL Memorandum Report 5828 (SECRET), August 1986.

9) Toward a National Strategy for High Power Microwave Directed Energy, W. M. Manheimer, Third High Power Microwave Meeting, sponsored by AFWL, Albuquerque, NM, December 1986.

10) An Artificial Over the Horizon Radar for Ship Defense (Confidential), W. M. Manheimer and W. A. Ali, NRL Memorandum Report 5953, to be published.

11) Submillimeter Wave Imaging Radar for SDI Midcourse Decoy Discrimination, W. M. Manheimer, NRL Memorandum Report 5954, to be published, and Journal of Defense Research, to be published.

Invited Presentations A: Invited Talks at Scientific Meetings

1) Weak Turbulence Theory of Velocity Space Diffusion in a Magnetic Field. NATO Conference on Plasma Waves in Space and the Laboratory, Roros, Norway, April 1968.

2) The Gas Embedded Z Pinch as a Fusion Reactor, APS Meeting, Monterrey, Calif., November 1972.

3) Reflected Particles and Ion Acoustic Shocks. International Conference on Waves and Instabilities in Plasmas, Innsbruck, Austria, April 1973.

4) The Marginal Stability Approach to Anomalous Transport, APS Meeting, Washington, D.C., April 1977.

5) Marginal Stability Transport, High Beta Workshop, Varenna, Italy, September 1977.

6) Anomalous Transport from Plasma Waves, XIVth International Conference on Phenomena in Ionized Gases. Grenoble, France, July 1979.

7) Studies of Laser-Plasma Interactions, Emphasizing Ablative Acceleration of Thin Foils, J. A. Stamper, S. E. Bodner, J. Boris, D. G. Colombant, R. Decoste, R. H. Lehmberg, S. H. Gold, J. Grun, W. M. Manheimer, E. A. McLean, J. M. McMahon, D. J. Nagel, S. P. Obenschain, J. P. Orens, B. H. Ripin, R. R. Whitlock and F. C. Young, presented at the Fifth Workshop on Laser Interaction and Related Plasma Phenomena, 5-9 November 1979, Rochester, New York.

8) Tokamak Heating and Current Drive with Intense Pulsed Ion Beams, APS Conference, San Diego, Calif., November 1980.

9) Theory and Simulation of Self Consistent Equilibrium and Adiabatic Evolution of High Current Electron Rings, AGU Meeting, Baltimore, MD, June 1983.

10) New Theoretical Thrusts in Millimeter Wave Research, Tenth International Conference on Infrared and Millimeter Waves, Lake Buena Vista, Florida, December 1985.

11) Theory of Radiation Sources Having Non-Circular Electron Orbits, IEEE Meeting on Plasma Science (High Power Microwave Minicourse), Saskatoon, Saskatchewan, Canada, May 1986.

12) High Voltage K_a-Band Gyrotron Oscillator Experiment, S. H. Gold, A. W. Fliflet, W. M. Manheimer, W. M. Black, V. L.

Granatstein, A. K. Kinkead, D. L. Hardesty and M. Sucy, Thirteenth IEEE International Conference on Plasma Science, Saskatoon, Saskatchewan, Canada, 19-21 May 1986.

13) A Free Electron Laser with a Rotating Quadrupole Wiggler, International Conference on Infrared and Millimeter Waves, B. Levush, T. M. Antonsen and W. M. Manheimer, Pisa, Italy, 1986.

14) Ultra-High Peak Power Millimeter-Wave Gyrotrons, A. W. Fliflet, S. H. Gold, W. M. Manheimer, W. M. Black and V. L. Granatstein, 1986 Microwave Power Tube Conference, Naval Postgraduate School, Monterey, California, 12-14 May 1986.

15) The NRL Quasi-Optical Gyrotron Program, W. M. Manheimer, DOE-DOD symposium on millimeter waves, NRL, April 1987.

16) The NRL Phase Locked Gyrotron, W. M. Manheimer, SDI Symposium on High Power Microwave Sources, Huntsville, Alabama, May 1987.

Invited Presentations B: Seminars at Laboratories and Universities

Numerous (3 or more) invited seminars at: NRL, MIT, University of Maryland, Cornell University, Columbia University, Los Alamos National Laboratory, Lawrence Livermore National Laboratory, Culham Laboratory, Princeton Plasma Physics Laboratory.

Other Recent Talks and Seminars:

Fontenay and Roses, France:
Marginal Stability Transport; and Ion Beams in Tokamaks (2 seminars, Nov 1977)

Ecole Polytechnique, Paliseau France, Nov 1978
Instability Induced Transport Inhibition in Laser Produced Plasmas

University of Tel Aviv Israel, Mar 1978
Anomalous Transport in Plasmas

Oxford University, Oxford, England, May 1978
Anomalous Transport in Laser Produced Plasmas

Free University, Brussels, Belgium, May 1978
Anomalous Transport in Laser Produced Plasmas

University of California at Los Angeles, May 1980
Tokamak Heating with Intense Pulsed Ion Beams

KMS Fusion, Ann Arbor, Michigan, April 1981
Stimulated Brillouin Backscatter in Laser Produced Plasmas

National Research Council, Ottawa, Canada, June 1981
Return Current Driven Ion Acoustic Instability in Laser Produced Plasmas

Lawrence Berkeley Laboratory, Berkeley, Calif., July 1981
Self Consistent Equilibrium and Adiabatic Evolution of an Electron Ring in a Modified Betatron.

New York University, New York, New York, April 1986
New Thrusts in Millimeter Wave Research.

Participation in Review Committees

December 1974	-	Review of the Los Alamos Reversed Field Pinch Program for the Department of Energy (AEC at the time)
September 1978	-	March 1979 - Review of the LINUS program at NRL for NRL
February 1979	-	Review of the effect of trapped particle instabilities on transport in tokamaks for the Department of Energy
July 1982	-	Review of tokamak current drive by intense pulsed electron beams for the Department of Energy
January 1983	-	Review of the NSWC program in intense beams for ONR
November 1985	-	Review of TRW Microwave Program for NRL
February 1986	-	Committee to assess the effectiveness of microwave directed energy, Harry Diamond Laboratories for DARPA.
May 1986	-	DARPA committee on high power microwave directed energy.
July 1986	-	Ad Hoc NRL working group on effect of electronic warfare on SDI.
November 1986	-	Office of the Secretary of Defense Committee on High Power Microwave directed energy (under Wahab Ali for John McCallum).

Organization of Scientific Meetings and Workshops

January 1977	-	Workshop on anomalous transport in tokamaks for the Department of Energy
May 1984	-	Organizing the Anomalous Absorption Conference - Charlottesville, Virginia

Honors

December 1967 -	Elected to Sigma Xi
December 1971 -	NRL Research Publication Award
April 1973 -	Quality Salary Increase
December 1974 -	NRL Research Publication Award
May 1975 -	Quality Salary Increase
August 1975 -	Outstanding Performance Award
October 1976 -	NRL Patent Award
June 1977 -	NRL Patent Award
September 1977-	September 1978 - One year study sabbatical at Culham Laboratory, Abingdon, England
November 1978 -	NRL Patent Award
November 1979 -	NRL Patent Award
March 1980 -	Quality Salary Increase
April 1980 -	NRL Patent Award
November 1980 -	Elected Fellow of American Physical Society
January 1981 -	Awarded Department of the Navy Meritorious Civilian Service Award
April 1981 -	NRL Patent Award
December 1982 -	$2,000 Merit pay performance award
November 1983 -	$1,500 Merit pay performance award
December 1984 -	$1,500 Merit pay performance award
December 1985 -	$1,300 Merit pay performance award
December 1985 -	NRL Patent Award
November 1986 -	$1,700 Merit pay performance award
December 1986 -	NRL Patent Award
January 1987 -	Nominated for group special achievement award for development of 100 MW gyrotron.
March 1987 -	NRL Invention Award
May 1987 -	Elected to Sigma Xi

Scientific Projects Managed

1) Toroidal Plasma Modeling, Department of Energy, Magnetic Fusion, $2,500K, October 1974 - October 1982. Developed theory of anomalous transport, drift and trapped particle instabilities, electron cyclotron and ion beam plasma heating, MHD instabilities.

2) Laser Fusion Modeling, Department of Energy through Code 4730, NRL, $1,500K, September 1972 - October 1984. Developed theory of parametric instabilities, anomalous transport, ablative acceleration and Rayleigh-Taylor instability.

3) High Power Gyrotron Development, ONR, October 1984 - October 1986, $1,000K. Developed 100 MW 35 GHz gyrotron, 8% efficiency using pulse power technology; developed phase locked gyrotron oscillator.

4) Disposable High Power Microwave Sources, Department of Energy through Lawrence Livermore National Laboratory, October 1984 - October 1986, $425K. Designed diode for disposable source and used resources to help support above experimental project.

5) Megawatt Gyrotron Development, Department of Energy, Office of Fusion Energy, October 1984 - October 1987, $1,200K. Designed and gave experimental demonstration of quasi-optical gyrotron.

6) 10 MW, 10 GHz Gyrotron Development Program, U. S. Army through Walter Read Army Medical Center, October 1984 - October 1987, $2,000K. Designed and started construction of 10 MW, 10 GHz gyrotron.

7) Plasma Microwave Sources, ONR, October 1986 - October 1991, $5,200K. Will investigate the effect of a background plasma on high power microwave tube performance, and the intense beam driven cyclotron auto resonance maser (CARM).

8) Testing of Vulnerability of Military Equipment to High Power Microwave Radiation, NAVSEA, $100K per year. Tested the vulnerability of a variety of military equipment to HPM at 10 and 35 GHz.

9) Microwave Directed Energy, SDIO-IST, February 1986 - January 1989, $1800K. Will produce 1 GW 35 GHz gyrotron and phase lock low power gyrotron by prebunching.

10) Laser Accelerators. SDIO-IST, June 1986 - October 1987, $230K. Will study and design experiment for microwave simulation of a laser accelerator.

11) Analysis of an Artificial Over the Horizon Radar, Oct 1986 - Oct 1987, $100K. Will analyze the prospect of radar scatter from microwave produced plasma for the purpose of ship terminal defense.

3. PUBLICATION LIST FOR ARNE W. FLIFLET

JOURNALS

1. "Photoionization Cross Section for the 4s Subshell of ZnI" by A.W. Fliflet, and H.P. Kelly, Phys. Rev. A, 10, 508 (1974).

2. Photoionization of the 4d Subshell of BaI" by A.W. Fliflet, R.L. Chase, and H.P. Kelly, J. Phys. B, 7, L443 (1974).

3. "The Position of the $4d^9 4f^1P$ Level Relative to the Ionization Limit in BaI" by J.E. Hansen, A.W. Fliflet, and H.P. Kelly, J. Phys. B, 8, L127 (1975).

4. "Oscillator Strengths of BaI$4d^9 4f$" by A.W. Fliflet, H.P. Kelly, and J.E. Hansen, J. Phys. B, 8, L268 (1975).

5. "Photoionization of the 3d, 3p, and 3s Subshells of ZnI", by A.W. Fliflet, and H.P. Kelly, Phys. Rev. A, 13, 312 (1976).

6. "Discrete Basis Set Calculation for e-N_2 Scattering Cross Sections in the Statis-Exchange Approximation" by A.W. Fliflet, D.A. Levin, M. Ma, and V. McKoy, Phys. Rev. A, 17, 160 (1978).

7. "Gaussian Matrix Elements of the Free Particle Green's Function" by D.A. Levin, A.W. Fliflet, M. Ma, and V. McKoy, J. Comp. Phys., 28, 416 (1978).

8. "Variationally Corrected Discrete Basis Set Calculation for Electron-Molecule Scattering in the Static-Exchange Approximation" by A.W. Fliflet, and V. McKoy, Phys. Rev. A, 18, 1048 (1978).

9. "Low-Energy Rotational and Vibrational-Rotational Excitation Cross Sections for H_2 by Electron Impact" by D.A. Levin, A.W. Fliflet and V. McKoy, Phys. Rev. A, 20, 491 (1979).

10. "Discrete Basis Set Method for Calculating Electron-Molecule Continuum Wavefunctions" by A.W. Fliflet and V. McKoy, Phys. Rev. A, 18, 2107 (1978).

11. "Distorted-Wave Approximation Cross Sections for Excitation of the $B^3\ \Sigma_u^+$ and $B^1\ \Sigma_u^1$ States of H_2 by Low-Energy Electron Impact," A.W. Fliflet, and V. McKoy, Phys. Rev. A, 21, 1863 (1980).

12. "Distorted-Wave Approximation Calculation for Excitation of the $B^3\ \Pi_g$, $C^3\ \Pi_u$, and $E^3\ {}_g\Sigma$States of N_2 by Low-Energy Electron Impact" by A.W. Fliflet, V. McKoy, and T.N. Rescingno, J. Phys. B, Atom. Molec. Phys. 12, 3281 (1979).

13. Low-Energy e - CO Scattering in the Static-Exchange Approximation" by D.A. Levin, A.W. Fliflet, and V. McKoy, Phys. Rev. A, 21, 1202 (1980).

14. "Dissociation of F_2 by Electron Impact Excitation of the 3 Lowest$^3\ {}_u\Pi$ Electronic State" by A.W. Fliflet, V. McKoy, and T.N. Rescigno, Phys. Rev. A, 21, 788 (1980).

15. "Circular-Electric Mode Waveguide Couplers and Junctions for Use in Gyrotron Traveling-Wave Amplifiers" by L.R. Barnett, J.M. Baird, A.W. Fliflet, and V.L. Granatstein, IEEE Trans. MTT MTT-28, 1477 (1980).

16. "Mode Coupling and Power Transfer in a Coaxial Sector Waveguide with a Sector Angle Taper" by A.W. Fliflet, L.R. Barnett and J.M. Baird, IEEE Trans. MTT MTT-28, 1482 (1980).

17. "Use of Weakly Irregular Waveguide Theory to Calculate Eigenfrequencies, Q Values, and RF Field Functions for Gyrotron Oscillators" by A.W. Fliflet and M.E. Read, Int. J. Electronics, 51, 475 (1981).

18. "A Self-Consistent Field Theory for Gyrotron Oscillators: Application to a Low Q Gyromonotron" by A.W. Fliflet, M.E. Read, K.R. Chu, and R. Seeley, Int. Journal of Electronics, Vol. 53, No. 6, 505 (1982).

19. "Use of Electrode Synthesis Technique to Design MIG-Type Guns for High Power Gyrotrons" by A.W. Fliflet, A.J. Dudas, M.E. Read, and J.M. Baird, Int. Journal of Electronics, Vol. 53, No. 6, 743 (1982).

20. "Mode Competition, Suppression, and Efficiency Enchancement in Overmoded Gyrotron Oscillators", by Y. Carmel, K.R. Chu, D. Dialetis, A. Fliflet, M.E. Read, K.J. Kim, B. Arfin, and V.L. Granatstein, Int. Journal of Infrared and Millimeter Waves, Vol. 3, No. 5, 645 (1982).

21. "High Voltage Ka-Band Experiment", by S.H. Gold, A.W. Fliflet, W.M. Manheimer, W.M. Black, V.L. Granatstein, A.K. Kinkead, D.L. Hardesty, and M. Sucy, IEEE Trans. Plasma Science, Vol. PS-13, No. 6, 374 (1985).

22. "Theory of Multi-cavity Gyroklystron Amplifier Based on a Green's Function Approach", A.K. Ganguly, A.W. Fliflet, and A.H. McCurdy, IEEE Trans. Plasma Science, Vol. PS-13, No. 6, (1985).

23. "Parametric Behavior of a High Gain 35-GHz Free Electron Laser Amplifier with Guide Magnetic Field," S.H. Gold, A.K. Ganguly, H.P. Freund, A.W. Fliflet, V.L. Granatstein, D.L. Hardesty and A.K. Kinkead, Nucl. Instrum. and Methods in Phy Research, A250, 366 (1986).

24. "One Dimensional Models for Relativistic Electron Beam Diode Design," J.M. Finn, A.W. Fliflet and W.M. Manheimer, Intl. J. Elect. 61 No. 6, 985 (1986).

25. "Linear and Nonlinear Theory of the Doppler-Shifted Cyclotron Resonance Maser Based on TE and TM Waveguide Modes," A.W. Fliflet, Intl. J. Elect. 61 No. 6, 1049 (1986).

26. "High Peak Power K_a-Band Gyrotron Oscillator Experiment," S.H. Gold, A.W. Fliflet, W.M. Manheimer, R.B. McCowan, W.M. Black, R.C. Lee, V.L. Granatstein, A.K. Kinkead, D.L. Hardesty and M. Sucy, Phys. Fluids (1987).

NRL MEMORANDUM REPORTS

1. "Scaling Calculations for a Relativistic Gyrotron", A.W. Fliflet, NRL Memorandum Report 5598 (1985).

2. High Voltage K_a-Band Gyrotron Experiment", S.H. Gold, A.W. Fliflet, W.M. Manheimer, W.M. Black, V.L. Granatstein, A.K. Kinkead, D.L. Hardesty and M. Sucy, NRL Memorandum Report 5682 (1985).

3. "One Dimensional Models for Relativistic Electron Beam Diode Design", J.M. Finn, A.W. Fliflet, and W.M. Manheimer, NRL Memorandum Report 5727 (1986).

4. "Linear and Nonlinear Theory of the Doppler-shifted Cyclotron Resonance Maser Based on TE and TM Waveguide Modes," A.W. Fliflet, NRL Memorandum Report 5812, (1986).

5. "Self-consistent Field Model for the Complex Cavity Gyrotron," A.W. Fliflet, R.C. Lee and M.E. Read, NRL Memorandum Report 5881 (1987).

6. "High Peak Power K_a-Band Gyrotron Oscillator Experiment," S.H. Gold, A.W. Fliflet, W.M. Manheimer, R.B. McCowan, W.M. Black, R.C. Lee, V.L. Granatstein, A.K. Kinkead, D.L. Hardesty and M. Sucy, NRL Memorandum Report 5923 (1987).

BOOK CHAPTERS

1. "T-Matrix Discrete Basis Set Method for Electron-Molecule Scattering in Electron-Molecule and Photon-Molecule Collision Processes," edited by T. Rescigno, V. McKoy, and B. Schneider Plenum 1979.

PUBLISHED ABSTRACTS OF CONTRIBUTED PAPERS

1. "Self-Consistent Approach to the Electron Beam - RF Field Interaction in Gyromonotron Oscillators", by A.W. Fliflet, J.M. Baird and M.E. Read, Bull. Am. Phys. Soc. 26, 847 (1981).

2. "Operation of Gyrotrons with Very Low Q Cavities", by M.E. Read, A.W. Fliflet, and K.R. Chu, Bull. Am. Phys. Soc. 26, 909 (1981).

3. "Operation of Gyromonotron with Low Q Factors", by A.W. Fliflet, M.E. Read, and R. Seeley, Technical Digest of the 1981 IEEE Int. Electron Devices Meeting, Washington, D.C., Dec. 7-9, 1981.

4. "Self-Consistent Field Effects in Gyromonotrons" by A.W. Fliflet, K.R. Chu, and M.E. Read, Bull. Am. Phys. Soc. 27, 1073 (1982).

5. "An Experimental Study of a Quasi-Optical Gyrotron for Fusion Applications", S.Y. Park, M.E. Read, R. Seeley, A. Fliflet, G.L. Bergeron, K.J. Kim, and V.L. Granatstein, Conference Record, IEEE International Conference on Plasma Science, San Diego, California, May 23-25, 1983.

6. "A 94 GHZ, 1 Megawatt Gyrotron", K. Busby, G. Bergeron, A. Dudas, A.W. Fliflet, K. Killian, M. NaGurney, J. Condon, M. Rhinewine, and M.E. Read, Conference Record, IEEE Int. Conf. on Plasma Science, San Diego, California, May 23-15, 1983.

7. "Self-Consistent RF Field Approach for Complex Cavity Gyrotrons", A.W. Fliflet, R. Lee, and M.E. Read, Bull Am. Phys. Soc. 28, 1060 (1983).

8. "Design of High Power Gyrotron Oscillators with Complex Cavity Structure", D. Dialetis, A.W. Fliflet, M.E. Read, and K.R. Chu, Bull. Am. Phys. Soc. 28, 1060 (1983).

9. "94 GHz Gyrotrons", K. Busby, J. Condon, G. Bergeron, M. Rhinewine, A. Fliflet, R. Lee and M. Read, Bull. Am. Phys. Soc. 28, 1193 (1983).

10. "Self-Consistent Field Approach for Complex Cavity Gyrotrons", A.W. Fliflet, M.E. Read, and R. Lee, Conference Digest, 8th Int. Conf. on Infrared and Millimeter Waves, Miami Beach, Florida, Dec. 12-17, 1983.

11. "Design of High Power Gyrotron Oscillators with Complex Cavity Structure", D. Dialetis, A.W. Fliflet, M. Read, and K.R. Chu, Conference Digest, 8th Int. Conf. on Infrared and Millimeter Waves, Miami Beach, Florida, Dec. 12-17, 1983.

12. "Slotted Gyrotron Cavities", K.O. Busby, A.W. Fliflet, and M.E. Read, Conference Digest , 8th International Conf. on Infrared and Millimeter Waves, Miami Beach, Florida, Dec. 12-17, 1983.

13. "TE_{1n} Gyrotrons", Busby, Condon, Killian, Rhinewine, Fliflet, Read, Bergeron, and Lee, 8th Int. Conf. on Infrared and Millimeter Waves, Miami Beach, Florida, Dec. 12-17, 1983.

14. "Self-Consistent RF Field Approach for Complex Cavity Gyrotrons", R. Lee, A.W. Fliflet, and M.E. Read, Conference Record, IEEE Int. Conf. on Plasma Science, St. Louis, Missouri, May 14-16, 1984.

15. "Large Signal Analysis for High-Power Gyro-Klystron Amplifiers", W.M. Bollen, A.K. Ganguly, B. Arfin, and A.W. Fliflet, Conference Record, IEEE Int. Conference on Plasma Science, St. Louis, Missouri, May 14-16, 1984.

16. "Recent Progress at NRL on High Power Gyrotron Oscillators for Fusion Applications", M.E. Read, A.W. Fliflet, T. Hargreaves, K. Busby, D. Dialetis, J. Levine, R. Lee, R. Seeley, G. Bergeron, and J. Burket, presented at the Symposium on Gyrotron Development, Lausanne, Switzerland, 4-6 July, 1984.

17. "Self-Consistent RF Field Approach for Complex Cavity Gyrotrons", R. Lee, A.W. Fliflet, and M.E. Read, presented at the Symposium on Gyrotron Development, Lausanne, Switzerland, July 4-6, 1984.

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